International Trade, Technology Diffusion, and the Role of Diffusion Barriers

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Abstract

This paper assesses the welfare impact of trade and technology diffusion as well as the change in the cross-country distribution of GDP due to removal of trade costs and diffusion barriers. The model extends the multi-country Ricardian trade model of Alvarez and Lucas (2007) to include technology diffusion with diffusion barriers. A key feature of the model is that some countries export goods produced by foreign technology via diffusion. The model is calibrated to match the world GDP distribution, the merchandise trade and technology diffusion shares of GDP, and real GDP per capita for a sample of 31 countries. Data on international trade in royalties, license fees, and information intensive services are used as proxies for international technology diffusion. There are three key findings. First, the welfare gains from removing diffusion barriers are 4–60% across countries, generally larger than the gains from removing trade costs (8–40%). The main reason is that diffusion has a larger impact on the nontradable sector due to the substitutability between trade and diffusion in the tradable sector. Another reason is that diffusion barriers are generally larger than trade costs. Second, removing trade costs and diffusion barriers has little impact on reducing the dispersion of real GDP per capita (measured by Gini index) across countries. Compared to the benchmark, free diffusion decreases the Gini by 4%, and free trade decreases the Gini by 2%. Third, removing diffusion barriers increases trade, which indicates that diffusion may enhance trade.

JEL: F15, F17, O11, O33, O40
Keywords: trade, technology diffusion, diffusion barriers, trade costs, welfare gains, GDP distribution, knowledge trade

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1 Introduction

International technology diffusion has become increasingly important over the past twenty years. While precise measures of international technology diffusion are lacking, the available data reveal rapid growth. For example, the value of international trade in royalties and license fees has increased by a factor of eleven over the last two decades.[1] In some developed countries, trade in royalties and license fees has been reported as the second most important category among the aggregate service categories (Breinlich and Criscuolo, 2011).[2] Combined with trade in information intensive services, the world total value of payments associated with international technology diffusion now equals 14% of world merchandise trade.[3] Moreover, the magnitude of technology diffusion as percentage of gross domestic product (GDP) is significant: payments associated with inward technology diffusion are as large as 16.3% of GDP in Ireland and average 4% of GDP across developed and emerging market economies.[4]

Technology diffusion is important, because it not only changes the productivity of goods produced for domestic markets, but it also opens up the exporting scope for the benefiting countries. An example of this is a DVD player, which is typically licensed to a Chinese manufacturer and then exported abroad. In 2002, Chinese firms typically paid $15-$20 per player in license fees and in turn were responsible for 70% of the world DVD player output.[5] Not surprisingly, China was the top exporter of DVD players. Benefiting from international technology diffusion, China became the biggest exporter of Information, Communication, Technology (ICT) goods in 2004.[6] Clearly, without technology diffusion, significantly different trade patterns would have occurred.

Motivated by its increasing importance, I investigate international technology diffusion in the presence of international trade in this paper to allow for the potential impact of diffusion on trade. The purpose of this paper is to assess and compare the welfare impact of international trade and technology diffusion. This paper also aims to quantify the change in the cross-country distribution of GDP due to reduction in trade costs for goods and removal of barriers to technology diffusion.

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[1] Data source: UNCTAD Handbook of Statistics (2008).

[2] The United Kingdom (UK), the world's second largest services exporter, reported that the value of exports and imports of royalties and license fees is approximately 23% and 26%, respectively, of total trade in services between 2000 and 2005 in the UK (Breinlich and Criscuolo, 2011).

[3] Data source: UNCTAD Handbook of Statistics (2008).

[4] The payments associated with inward technology diffusion in this paper refer to those through imports of royalties, license fees, and information intensive services. The sample contains 31 countries. See Data Description and Figure 2 in Section 4 for more details.

[5] Producers of DVD players need to pay license fees to the patent holders of the DVD technology (Sony, Philips, Toshiba and Time Warner) as well as for MPEG-2 licences.

[6] Data source: OECD, ITS database.

To accomplish this, two questions are posed. First, how large are diffusion barriers and trade costs across countries? Second, given the current level of trade costs and diffusion barriers, how important is their elimination in terms of the change in welfare and the cross-country distribution of GDP?

To answer these questions, this paper develops and calibrates a general equilibrium model in which countries interact through trade in goods and diffusion of technology. The model extends the multi-country Ricardian trade model of Eaton and Kortum (2002) and Alvarez and Lucas (2007) to include diffusion of knowledge.[7] In the classic Ricardian trade literature, technology is implicitly assumed to be exclusive to each country; thus, there is no room for technology diffusion in the status quo. To model technology diffusion, I differentiate between two types of technologies in each country: exclusive technologies, which are available only to the home country, and diffusive technologies, which are available in all countries due to technology diffusion.

To investigate the magnitude of diffusion, I introduce barriers to technology diffusion because barriers play a key role in determining volumes of diffusion. Similar to merchandise trade, technology diffusion in the model is limited by "iceberg" diffusion barriers. This assumption is consistent with the empirical evidence on the existence of significant barriers to international knowledge diffusion. For example, Peri (2005) examines the role of different borders, languages, and technological differences, and Li (2009) investigates the changing pattern of border and distance effects in knowledge flows.

The model has two sectors: a tradable sector, which produces intermediate goods, and a nontradable sector, which produces final consumption goods. The key departure from Alvarez and Lucas (2007) is that both sectors are open to technology diffusion. Diffusion enlarges the set of available technology for each country and potentially increases productivity. With diffusion, productivity is determined by the domestic technology in the production country plus the diffusive technology from abroad. Between each country pair, there exist trade costs and diffusion barriers. Representative agents in each country shop around the world to find the least costly method of obtaining tradable and nontradable goods. An equilibrium outcome is that some countries (intermediaries) export goods produced by foreign technology via diffusion. For example, an intermediary country i might use diffusive technology from country j in production to achieve higher productivity

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[7] "Diffusion of knowledge" and "technology diffusion" are interchangeably used in this paper. Knowledge is any intellectual input which serves to produce goods. A blueprint, an industrial design, a process redesign, and technical support are all examples of knowledge. Eaton and Kortum (2005) use the word "ideas" as "the fundamental atom of technology". In this paper, I use "knowledge" or "technology".

and then export to country n. This process entails diffusion barriers from country j to i and trade costs from country i to n. Allowing for countries to interact through both merchandise trade and technology diffusion enriches the international merchandise trade pattern in the model and enables the model to generate both merchandise trade and technology diffusion volume consistent with the data.[8]

To quantitatively assess the current level of diffusion barriers and trade costs as well as their welfare impact, I calibrate the model to match the merchandise trade share, the technology diffusion share, the size of GDP, and the real GDP per capita for a sample of 31 countries.[9] Data on international trade in royalties, license fees, and information intensive services are used as proxies for international technology diffusion. The calibrated model has explanatory power of at least 95% for all variables of interest.[10]

There are three key findings. First, the welfare impact of technology diffusion is generally larger than that of merchandise trade. Removing diffusion barriers in the benchmark increases welfare by 4–60% across countries, while removing merchandise trade costs increases welfare by 8–40%. The main reason is that technology diffusion has a larger impact on the nontradable sector due to the substitutability between merchandise trade and technology diffusion in the tradable sector. That is, obtaining foreign technology to produce goods locally decreases the incentive to import goods. Because technology diffusion substitutes for merchandise trade, diffusion of technology benefits a nontradable sector more so than it does a tradable sector. Another reason is that the technology diffusion barriers are larger than merchandise trade costs for most countries. I also perform another counterfactual exercise to compare the difference in welfare between the benchmark model and a hypothetical autarkic world. This experiment informs us of the current level of welfare gains from diffusion and trade. I find that abolishing trade leads to larger welfare losses than does abolishing diffusion. This implies that the welfare improvement of moving from prohibitive trade costs to the benchmark is larger than that of moving from prohibitive diffusion barriers to the benchmark. This in turn suggests that, currently, the world has exploited more of the potential gains from reductions in the barriers to merchandise trade than the potential gains from reductions in the barriers to technology diffusion. This calls for more attention to be paid to the reduction of diffusion barriers.

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[8] In a model without technology diffusion, the correlation coefficient between the model generated merchandise trade and the data is 0.59, as in Alvarez and Lucas (2007). My model generates the correlation as high as 0.92 for merchandise trade share (as a percentage of a country's GDP).

[9] The sample includes most OECD countries and main emerging economies. The selection criteria is explained in Section 4.1.

[10] A measure of the explanatory power of the model is given by $R_H^2 = 1 - \frac{\sum_{i=1}^{I}\left(\tilde{H}_i^{data} - \tilde{H}_i^{model}\right)^2}{\sum_{i=1}^{I}\left(\tilde{H}_i^{data}\right)^2}$.

Second, I find that free merchandise trade and free technology diffusion increase real GDP per capita by 5–30% and 4–55%, respectively. In both cases, the dispersion of real GDP per capita across countries is reduced. The Gini index of real GDP per capita is decreased by 4% due to moving from the benchmark to free technology diffusion and by 2% due to moving from the benchmark to free merchandise trade. This is consistent with the result that free technology diffusion generates larger gains than does free merchandise trade.

Third, removing diffusion barriers increases merchandise trade because countries achieve higher productivity from obtaining foreign technology via diffusion and therefore improve their ability to export to the global market. This finding implies that diffusion may enhance trade and thus is different from the literature because most existing trade models predict that diffusion is a substitute for trade: if one can use the technology of one's trading partners, then there is less need for trade (Chaney, 2008). However, in this paper, due to the existence of intermediary countries who benefit from lower diffusion barriers and greater diffusion volumes, removal of diffusion barriers eventually increases trade. This result is also consistent with the first two findings because removing diffusion barriers has "spillover" effects on merchandise trade. In summary, free technology diffusion has greater welfare impact and contributes more to reducing the dispersion of real GDP per capita than does free merchandise trade.

These findings contribute to the emerging literature simultaneously examining trade and technology diffusion (e.g., Eaton and Kortum, 2006; Rodríguez-Clare, 2007; Chaney, 2008).[11] This literature models technology diffusion as a global pool without diffusion barriers or trade costs for diffusion and do not use data associated with technology diffusion to quantify the gains. However, as pointed out by Keller (2004), there is no indication of the existence of a global pool of technology, and knowledge can only be partially codified in diffusion. Thus, I introduce barriers to technology diffusion and quantitatively assessed their importance. Additionally, technology diffusion involves both market transactions and externalities and is difficult to measure in the data (Keller, 2004). Therefore, quantifying the gains from diffusion represents a significant challenge (Ramondo and Rodríguez-Clare, 2010). In calibrating the model, I use market transaction data (captured by trade in royalties, license fees and information intensive services) to measure technology diffusion, which yields a lower bound of real gains from technology diffusion. My results can be compared with the literature on gains from global diffusion without diffusion barriers. This literature usually pursues an indirect approach based on an application of the semi-endogenous growth model to

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[11] Grossman and Helpman (1991) is an early exception.

quantify the importance of diffusion. For example, Rodríguez-Clare (2007) based his work on the growth rate of a country and calculated the upper bound of the overall gains from both trade and diffusion to be between 206% and 240% for a country with approximately 1% of the world's GDP. My results for overall gains from trade and diffusion for a similar country are around 69–73%. It is not surprising that the gains from diffusion in this paper are smaller than those in Rodríguez-Clare (2007) because I model diffusion differently and use market transaction data to directly quantify the gains from diffusion. This helps to understand and dissect the gains from technology diffusion through different channels.

The model structure in the present paper comes close to another branch of relevant literature which quantifies the importance of multinational production (MP). The state-of-the-art works on MP include Ramondo and Rodríguez-Clare (2009, 2010), Irarrazabal et al. (2009), and Arkolakis et al. (2011). Ramondo and Rodríguez-Clare (2009) incorporate MP into the model of trade by allowing a country's technologies to be used for production abroad through multinational affiliates and explore the relation between MP and trade. Irarrazabal et al. (2009) introduce intra-firm trade into Helpman, Melitz and Yeaple (2004) to explore the correlation between trade and MP flows. Intra-firm trade is important in MP since multinational affiliates often import goods from their home countries. In this paper, however, I use trade in royalties and license fees to proxy for technology diffusion. While part of trade in royalties and license fees is probably attributed to intra-firm transactions, a large part of it presumably is not. Therefore, the present framework captures the diffusion of foreign technologies to non-affiliated indigenous firms, which MP does not capture. For example, if U.S. technologies are used for production in Canada by non-affiliated Canadian firms, this way of sharing technologies across countries cannot be captured by MP but is partly captured by trade in royalties and license fees.[12] In fact, trade in royalties and license fees covers the exchange of payments and receipts associated with technology transfer between residents and nonresidents, whether or not it belongs to intra-firm trade. Hence, my approach provides a different proxy for technology diffusion. Whether intra-firm trade or trade in royalties and license fees represents a better proxy for technology diffusion is not clear, but the two approaches are complementary to each other. As Ramondo and Rodríguez-Clare (2010) point out, much more attention should be devoted to understanding where the gains of diffusion come from and which are the main barriers to diffusion. This paper therefore provides a new approach on quantifying the gains from diffusion.

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[12] Here, the word "partly" emphasizes that only the part associated with market transactions can be captured by the data.

This paper is also related to the empirical literature examining the role of borders, physical distance, languages, technological differences, and other factors determining knowledge flows (e.g., Peri, 2005; Li, 2009). These empirical studies use patent citation data as a proxy for knowledge flows and mainly capture the barriers to externalities in technology diffusion through knowledge spillovers. This paper uses a general equilibrium model to quantitatively assess the barriers to technology diffusion based on detailed data on market transactions of technology (e.g., royalties and license fees). This allows us to use a fully-specified model to make predictions on all variables of interest and to investigate the interactions between merchandise trade and technology diffusion.

Finally, this paper provides new insights into the recent literature exploring the potential gains from liberalizing merchandise trade in Ricardian models (Alvarez and Lucas, 2007; Waugh, 2010). The welfare gains of moving from total isolation to free trade and free diffusion are more than double the gains of moving from total isolation to free trade alone. On the other hand, I obtain very similar magnitude of gains of moving from total isolation to free trade alone to that obtained by Alvarez and Lucas (2007). For example, they calculated the upper bounds of gains of moving from autarky to free trade in terms of consumption equivalence for the U.S., Japan, and Denmark to be 10%, 14%, and 38% respectively. My results for the gains of moving from autarky to free merchandise trade for these three countries are 10%, 15%, and 36% respectively. When both diffusion and trade are allowed for, the overall gains are larger: 15% for the U.S., 25% for Japan, and 77% for Denmark. Here small countries benefit more than large countries from both merchandise trade and technology diffusion because of the market size effect: large countries (in terms of GDP size) already enjoy big domestic markets, which limits the potential gains from free trade and diffusion.

The remainder of the paper is organized as follows. Section 2 presents a model of trade and technology diffusion with one tradable sector to illustrate the mechanism and intuition. Section 3 develops the full model with both tradable and nontradable sectors and analyzes the general equilibrium. Section 4 describes the data and calibration procedure as well as the benchmark results. Section 5 presents the quantitative results from counterfactual exercises. Section 6 concludes.

2 A Model of Trade and Technology Diffusion

This section presents a model with tradable goods to illustrate the mechanism and intuition. The full model with both tradable and nontradable goods is presented in Section 3.

2.1 Environment

There are I countries indexed by $i \in \{1, ..., I\}$ endowed with L_i units of labor (the only factor of production). Each country produces a continuum of tradable goods indexed by $u \in [0, 1]$. A representative agent consumes a continuum of goods u in quantities $q(u)$ to maximize a CES utility

$$U = \left[\int_0^1 q(u)^{\frac{\sigma-1}{\sigma}} du \right]^{\frac{\sigma}{\sigma-1}} \tag{2.1}$$

with elasticity of substitution $\sigma > 0$.

Let c_i denote the unit cost of input in country i. In this section, the unit cost of input c_i is simply equal to the wage rate w_i since labor is the only factor of production.[13] As in Eaton and Kortum (2002), country i's efficiency in producing good u is denoted as $z_i(u)$. With constant returns to scale, the unit cost of producing good u in country i is then $c_i/z_i(u)$. Following Alvarez and Lucas (2007), I work with the inverse of productivity, the cost parameter $x_i(u)$ where $x_i(u)^{-\theta} = z_i(u)$. $x_i(u)$ is the cost parameter associated with country i's technology to produce good u. The unit cost of producing good u in country i is then $x_i(u)^{\theta} c_i$, where $\theta > 0$ is a common parameter across goods and countries that amplifies the effect of variability of cost parameter.[14]

The model without technology diffusion follows Eaton and Kortum (2002) and Alvarez and Lucas (2007). The cost parameters x_i for each good u are assumed to be random variables, which are drawn from a distribution that depends upon the total stock of knowledge in country i. This corresponds to the economy's productivity for a good u which is determined by the best knowledge available for the production of this good.[15] It is easy to show that x_i is distributed exponentially with parameter λ_i, $x_i \sim exp(\lambda_i)$, where λ_i is the stock of knowledge located in country i and λ_i is also called technology state parameter.[16] As in Alvarez and Lucas (2007), country i's productivity is only determined by its own knowledge stock λ_i; that is, technology is exclusive to its home

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[13] I use the notation c_i here to facilitate the comparison with the full model in Section 3.

[14] The two approaches in Eaton and Kortum (2002) and in Alvarez and Lucas (2007) are equivalent except for the definition of θ. The θ in this paper, as in Alvarez and Lucas (2007), is the inverse of Eaton and Kortum's θ. Hence, in this paper the higher θ, the larger dispersion of the productivity distribution.

[15] As in Eaton and Kortum (2005), the fundamental atom of technology is an idea ("a piece of knowledge") which is just a recipe to produce good u with some efficiency z. Knowledge for producing a particular good differ only in terms of a "quality" parameter.

[16] This result comes from having λ stock of knowledge for each good (each associated with a cost parameter), all of which are independently drawn from an exponential distribution with parameter 1. Then, the distribution of the best knowledge is exponential with parameter λ. The mathematical derivation is as below. Let q represent the quality of knowledge, then $Pr(Q \leq q) = H(q) = 1 - 1/q$. Let v be the quality of the best knowledge that has arrived up to time t, then using $e^x \equiv \sum_{k=0}^{\infty} x^k/k!$ we get $Pr(V \leq v) = \sum_{k=0}^{\infty} (e^{-\lambda}(\lambda)^k/k!) H(v)^k = e^{-\lambda/v}$, and hence, $x \equiv 1/v \sim exp(\lambda)$. See Kortum (1997) and Rodríguez-Clare (2007).

country.

In order to incorporate technology diffusion, I differentiate between two types of technologies in each country: exclusive technologies, which are available only to its home country, and diffusive technologies, which are available to all countries due to technology diffusion. Let x_i^E and x_i^D denote the cost parameters associated with exclusive and diffusive technologies. Assume x_i^E and x_i^D are independently drawn from exponential distribution with parameters λ_i^E and λ_i^D, respectively. This is equivalent to dividing each country's domestic stock of knowledge λ_i into two components: exclusive knowledge λ_i^E and diffusive knowledge λ_i^D, where $\lambda_i = \lambda_i^E + \lambda_i^D$. In other words, exclusive knowledge is limited to domestic production in its home country, while diffusive knowledge is migrating across national borders. Without technology diffusion, each country's productivity is only determined by its domestic knowledge stock. Hence, the lowest cost of production in country i is $\min\{(x_i^E)^\theta c_i, (x_i^D)^\theta c_i\}$ where $x_i = \min\{x_i^E, x_i^D\}$ and $x_i \sim exp(\lambda_i)$ by the property of exponential distribution.[17] With technology diffusion, the scale of the set of available knowledge for each country is enlarged. Country i can therefore obtain the lowest costs of production from both its own technology, which is associated with its own knowledge stock λ_i, and the diffusive technology from other countries λ_j^D $(j \neq i)$ because only diffusive technology can be used in foreign countries. This means that country i can obtain the cost parameter x_j^D associated with λ_j^D $(j \neq i)$ via technology diffusion.

Next I introduce barriers to technology diffusion because barriers play a key role in determining trade volumes. Consider a tradable good u produced in country m. This good can be produced with the productivity determined by country m's own technology at unit cost $x_m(u)^\theta c_m$. Good u can also be produced in country m with the productivity determined by foreign technology from country i $(m \neq i)$ through technology diffusion. But this process entails some barriers, denoted by b_{mi}. Diffusion barriers b_{mi} are country-pair specific costs associated with using diffusive technology from technology home country i to produce in country m. Similar to trade costs for goods, diffusion barriers are also modeled as "iceberg" costs: $b_{mi} < 1$ (if $m \neq i$), $b_{mi} = 1$ (if $m = i$), and $b_{mi} \geq b_{mj} b_{ji}$. Diffusion barriers only occur when diffusive technology is used by a country outside its home country. If the diffusive technology is used in its home country, no extra costs occur by assumption (i.e., $b_{ii} = 1$). Diffusion barriers can also be viewed as a discount factor which belongs to the interval $[0, 1]$, where b closer to 1 means lower barriers to diffusion and b closer to 0 means higher barriers. Taking into account technology diffusion with diffusion barriers, good u

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[17] The property is that if x and y are independent, $x \sim exp(\lambda)$ and $y \sim exp(\mu)$, then $\min\{x, y\} \sim exp(\lambda + \mu)$.

can also be produced in country m at unit cost $(x_i^D(u)^\theta c_m)/b_{mi}$. It uses the domestic input c_m in country m, but the cost parameter is associated with country i's diffusive technology, which has to be discounted by diffusion barriers between country i and m. I define $c_{mi} = c_m/b_{mi}$ for convenience. Hence the lowest cost to produce good u in country m is simply

$$\min\{x_m(u)^\theta c_m, \min_{i\neq m} x_i^D(u)^\theta c_{mi}\} = \min\left\{\left[x_m^E(u)\right]^\theta c_m, \min_i \left[\frac{x_i^D(u)}{b_{mi}^{1/\theta}}\right]^\theta c_m\right\} \tag{2.2}$$

2.2 Equilibrium

Following Alvarez and Lucas (2007), I relabel goods by the vector $x \equiv (x^E, x^D)$ rather than u where $x^E \equiv (x_1^E, x_2^E, ..., x_I^E)$ and $x^D \equiv (x_1^D, x_2^D, ..., x_I^D)$. Under perfect competition, the unit cost of a tradable good (x^E, x^D) produced in country m (intermediary country) with technology from country i and then shipped to country n is $(x_i^D)^\theta c_{mi}/k_{nm}$, where k_{nm} is "iceberg" trade cost for goods, with one unit of a good shipped from m resulting in $k_{nm} \leq 1$ units arriving in n (where $k_{nn} = 1$, and $k_{ni} \geq k_{nm}k_{mi}$ for all n, m, i). The price of the good (x^E, x^D) in country n is simply the minimum cost at which it can be obtained by n, namely

$$p_n(x^E, x^D) = \min\left\{\min_i \left[\frac{x_i^E}{k_{ni}^{1/\theta}}\right]^\theta c_i, \min_{i,m}\left[\frac{x_i^D}{b_{mi}^{1/\theta}k_{nm}^{1/\theta}}\right]^\theta c_m\right\} \tag{2.3}$$

The first term on the right-hand side (RHS) minimizes over all possible ways in which country n can procure the good conditional on using exclusive technology. Note that country n can benefit from the exclusive technology of other countries through importing the good produced by exclusive technology of other countries (i.e., $i \neq n$). The second term on the RHS minimizes over all possible ways in which country n can procure the good conditional on using diffusive technology from technology home country i to produce in an intermediary country m for all $\{i, m\}$ combinations. Note that country n can also benefit from the diffusive technology of other countries through either using diffusive technology from other countries to produce the good domestically (i.e., $i \neq m = n$) or importing the good produced by diffusive technology of other countries in an intermediary country (i.e., $m \neq n$ for all possible $\{i, m\}$). The first term is a standard term as in Eaton and Kortum (2002) and in Alvarez and Lucas (2007). The second term now emerges due to technology diffusion.

From the properties of the exponential distribution, it follows that $p_n(x^E, x^D)^{1/\theta}$ is distributed exponentially with parameter [18]

$$\phi_n \equiv \sum_i (\phi^E_{ni} + \phi^D_{ni}), \tag{2.4}$$

where $\phi^E_{ni} = (c_i/k_{ni})^{-1/\theta}\lambda^E_i$ and $\phi^D_{ni} = (\tilde{c}_{ni})^{-1/\theta}\lambda^D_i$, and $\tilde{c}_{ni} \equiv \min_m\{c_{mi}/k_{nm}\}$ is the minimum cost of the input for goods produced in country m using diffusive technology from i (taking into account all possible intermediary country m). Intuitively speaking, the price parameter ϕ_n summaries the effective technology that country n can tap into from all over the world, after taking into account the knowledge stocks around the world, the input costs around the world, trade costs, and diffusion barriers between n and other countries.

Given the distribution of prices across goods and CES preferences, the price index in country n, p_n is given by

$$p_n^{1-\sigma} = \int p_n(x^E, x^D)^{1-\sigma} dF(x^E, x^D)$$

where $F(x^E, x^D)$ is the joint distribution of x^E and x^D. Then, the price index in n is

$$p_n = C\phi_n^{-\theta}, \tag{2.5}$$

where $C = \Gamma(1 + \theta(1-\sigma))^{1/(1-\sigma)}$ is a constant, with $\Gamma()$ being the Gamma function.[19] As the effective technology available to n increases, consumers are better off.

As shown by Eaton and Kortum (2002), the average price charged by any country i in country n is the same. Moreover, by the properties of the exponential distribution, a share $\tau^E_{ni} \equiv \phi^E_{ni}/\phi_n$ of goods bought by country n will be produced by country i with its exclusive technology. Letting $X_n = w_n L_n$ denote total spending by country n, then

$$\tau^E_{ni} X_n \tag{2.6}$$

is the value of goods produced with exclusive technology in country i that are exported to country n. Similarly, $\tau^D_{ni} X_n = \frac{\phi^D_{ni}}{\phi_n} X_n$ is the value of goods consumed by n that are produced with diffusive technology from i. Note that those goods could be produced in any intermediary country $m \in \arg\min_j(\tilde{c}_{ji}/k_{nj})$. Let y^D_{nmi} be the share of the spending on goods produced in country m (then shipped to n) in total spending by country n on goods produced with diffusive technology from country i. We have $\sum_m y^D_{nmi} = 1$ since these are shares over all possible intermediary countries for

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[18] These properties are: (1) if $x \sim exp(\lambda)$ and $k > 0$ then $kx \sim exp(\lambda/k)$; and (2) if x and y are independent, $x \sim exp(\lambda)$ and $y \sim exp(\mu)$, then $\min\{x, y\} \sim exp(\lambda + \mu)$.

[19] Rodríguez-Clare (2007) explains why $1 + \theta(1-\sigma) > 0$ holds.

the pair $\{n, i\}$. In equilibrium, the following "complementary slackness" conditions must hold:

$$c_{mi}/k_{nm} > \tilde{c}_{ni} \Rightarrow y^D_{nmi} = 0$$

$$y^D_{nmi} > 0 \Rightarrow c_{mi}/k_{nm} = \tilde{c}_{ni}$$

The value of goods produced in m using diffusive technology from i for n is $\tau^D_{nmi} X_n$, where $\tau^D_{nmi} \equiv y^D_{nmi}\phi^D_{ni}/\phi_n$. Summing over i yields the total imports by n from m of goods produced with diffusive technology,

$$\sum_i \tau^D_{nmi} X_n \tag{2.7}$$

Using (2.6) and (2.7), imports of goods by n from i are

$$\left(\tau^E_{ni} + \sum_j \tau^D_{nij}\right) X_n = (\tau^E_{ni} + \tau^D_{nii}) X_n + \left(\sum_{j \neq i} \tau^D_{nij}\right) X_n \tag{2.8}$$

Thus, total imports of goods by n from $i \neq n$ are

$$M_{ni} = \left(\tau^E_{ni} + \sum_j \tau^D_{nij}\right) w_n L_n \tag{2.9}$$

Aggregate imports for country n are simply $M_n = \sum_{i \neq n} M_{ni}$. Trade balance conditions are

$$\sum_{i \neq n} M_{ni} = \sum_{i \neq n} M_{in} \tag{2.10}$$

The expression for total value associated with technology diffusion from country i to production country m is denoted by M^D_{mi}. This is associated with the value of goods produced by diffusive technology from country i to m and those goods are then shipped to all over the world. Summing up over all destination countries n yields

$$M^D_{mi} = \sum_n \tau^D_{nmi} X_n \tag{2.11}$$

A ***competitive equilibrium*** *is characterized by vectors of prices $p_n = (p_1, p_2, ..., p_I)$ and wages $w = (w_1, w_2, ..., w_I)$ such that, together with the vector $(\phi_1, \phi_2, ..., \phi_I)$, equations (2.4) and (2.5) are satisfied, the trade balance conditions (2.10) are satisfied, where a share τ^E_{ni} of goods bought by* *country n is produced by country i's exclusive technology, and a share* τ^D_{ni} *of goods bought by country n is produced by country i's diffusive technology. The technology diffusion condition is expressed by (2.11).*[20]

2.3 Some results under symmetry

To gain intuition on the mechanism of the model, consider the simple case of symmetric countries ($L_i = L$) and symmetric trade costs and diffusion barriers ($k_{ni} = k$ and $b_{ni} = b$ for all $n \neq i$), which can be solved analytically.

Symmetry yields $w_n = w$,$c_n = c$, $w = c$, and $p_n = p$. The unit cost of input using diffusive technology is $c_{mi} = c/b$ for all $m \neq i$. If the condition $k < b(< 1)$ is satisfied (i.e., diffusion barriers are smaller than trade costs since b is closer to 1 than k), then $y^D_{nmi} = 0$ for all $n \neq m$: there is no trade in goods produced with diffusive technology since barriers to technology diffusion are smaller than trade costs for goods, and so country n would prefer domestic production using foreign technology through diffusion rather than importing goods from intermediary countries. Hence, if $k < b$, there are no intermediary countries in this symmetric world.[21] From (2.5), the price level in any country is

$$p = C[\lambda + (I-1)(k^{1/\theta}\lambda^E + b^{1/\theta}\lambda^D)]^{-\theta} w \tag{2.12}$$

Intuitively, the term inside the squared brackets captures the effective knowledge, which can be enjoyed by consumers in any country: domestic stock of knowledge $\lambda = \lambda^E + \lambda^D$, exclusive knowledge from other countries taking into account trade costs for goods, $k^{1/\theta}$, and diffusive knowledge from other countries taking into account diffusion barriers, $b^{1/\theta}$. Consumers enjoy exclusive knowledge through importing tradable goods, and diffusive knowledge through technology diffusion to produce goods domestically.

Trade Flows The share that country n will devote to spending on goods produced in country $i \neq n$ with country i's exclusive technology is simply the contribution of country i's exclusive knowledge to the effective knowledge in country n. Thus, under symmetry it is

$$\tau^E = \frac{k^{1/\theta}\lambda^E}{\lambda + (I-1)(k^{1/\theta}\lambda^E + b^{1/\theta}\lambda^D)} \tag{2.13}$$

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[20] We use the normalization: $\sum_{i=1}^{I} w_i L_i = 1$.

[21] If diffusion barriers are larger than trade costs (i.e., $b < k$), there are no diffusion in this symmetric world, since wages are equalized. But in an asymmetric world, even if $b < k$, technology diffusion exists because countries try to benefit from lower wages in production countries.

Similarly, the share that n will spend on goods produced locally with diffusive technology via diffusion from country i is the contribution of i's diffusive knowledge to the effective knowledge in country n,

$$\tau^D = \frac{b^{1/\theta}\lambda^D}{\lambda + (I-1)(k^{1/\theta}\lambda^E + b^{1/\theta}\lambda^D)} \tag{2.14}$$

Now consider the effect of a change in diffusion barriers, captured by diffusion barrier parameter b, on trade flows. When b decreases (i.e., barriers to technology diffusion become larger), τ^E increases, which implies that merchandise import share of country n from country i increases with bilateral diffusion barriers. In this case, if there is no exclusive knowledge (i.e., all knowledge is diffusive, $\lambda^D = \lambda$), then $\tau^E = 0$. This is consistent with the prediction about the substitutability between merchandise trade and technology diffusion in traditional Ricardian models; that is, technology diffusion substitutes for merchandise imports in the tradable sector.

Welfare Gains For simplicity, assume $k < b$ (i.e., merchandise trade costs larger than diffusion barriers) in the benchmark. The gains from moving from isolation to openness based on the benchmark (the benchmark with trade in goods and technology diffusion), call it G_O, can be computed by comparing the changes in real wage, w/p. Under symmetry, wages are equalized across countries, hence they can be normalized to one. Then one only needs to compare prices across different scenarios to compare the welfare gains. The price index for the benchmark is given by (2.12), whereas the analogous result with isolation (no merchandise trade and no technology diffusion) is obtained by letting $k \to 0$ and $b \to 0$ in (2.12). This yields the price level under isolation

$$p_{ISO} = C\lambda^{-\theta} w$$

Hence, the proportional gains from openness ($\widetilde{G_O}$) are given by

$$\widetilde{G_O} = \frac{p_{ISO}}{p} = \left[\frac{\lambda + (I-1)(k^{1/\theta}\lambda^E + b^{1/\theta}\lambda^D)}{\lambda}\right]^\theta \tag{2.15}$$

or, $G_O = \ln(\widetilde{G_O})$. (Expressions for gains with a tilde represent proportional gains.) It is easy to see that the gains from openness G_O increases with k and b: the lower trade costs or the lower diffusion barriers, the larger the welfare gains from openness.

To compare the gains from trade and the gains from diffusion, I calculate gains from trade by computing the gains of moving from isolation to only trade (no diffusion), G_T. Analogously, I calculate gains from diffusion by computing the gains of moving from isolation to only diffusion (no trade), G_D. Then I derive the price index when there is only trade. From (2.12), by letting $b \to 0$, and allowing diffusive technology to be used for domestic production and trade, the price for only trade is

$$p_T = C\left[\lambda(1 + (I-1)k^{1/\theta})\right]^{-\theta} w$$

Gains from trade are then given by

$$\widetilde{G_T} = \frac{p_{ISO}}{p_T} = \left[1 + (I-1)k^{1/\theta}\right]^{\theta} \tag{2.16}$$

Hence, gains from trade (G_T) increase with the value of k, i.e., the smaller trade costs, the larger gains from trade. Similarly, the gains from diffusion (increase in real wage from isolation to only diffusion and no trade) are

$$\widetilde{G_D} = \frac{p_{ISO}}{p_D} = \left[\frac{\lambda + (I-1)b^{1/\theta}\lambda^D}{\lambda}\right]^{\theta} \tag{2.17}$$

The gains from technology diffusion (G_D) increase with b and the proportion of diffusive knowledge in total knowledge stock (λ^D/λ). This means that the smaller diffusion barriers and the larger share of diffusive knowledge, the larger gains from diffusion. Here gains from merchandise trade (G_T) do not depend on exclusive knowledge (λ^E), because it is implicitly assumed that without diffusion, all goods produced by domestic knowledge can be traded, while only diffusive knowledge is amenable to production in foreign countries through diffusion when countries are open to technology diffusion. Then the total gains from current openness are less than the sum of gains from both trade and diffusion ($G_O < G_T + G_D$), i.e., trade and diffusion behave like substitutes in this symmetric world, but the substitution effect is dampened by the diffusion barriers.[22]

It is worth noting that it is not always the case that gains from diffusion are greater than those from trade. Based on equation (2.16) and (2.17), if $b^{1/\theta}(\lambda^D/\lambda) > k^{1/\theta}$, gains from diffusion are larger than those from trade. But if the share of diffusive knowledge (λ^D/λ) is small, it could be that gains from trade are larger ($G_D < G_T$). There is a threshold level of diffusive knowledge $\overline{\lambda^D}$ in this symmetric case such that the gains from diffusion equal gains from trade. Even if all knowledge is diffusive (i.e., $\lambda^D/\lambda = 1$, each country has no exclusive knowledge), trade still exists due to the existence of diffusion barriers. Hence, the comparison of welfare gains from trade and diffusion depends on the trade-off between trade costs and diffusion barriers as well as the share of diffusive knowledge in overall knowledge stock.

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[22] Denote $\triangle = G_T + G_D - G_O$. It is easy to show that $\triangle$ decreases as b decreases to 0 (i.e., larger diffusion barriers).

3 Full Model: Tradable and Nontradable Sectors

This section extends the model by allowing for nontradable goods, which are also amenable to technology diffusion, and an input-output loop where intermediate goods are used for the production of other intermediate goods as in Alvarez and Lucas (2007). I first present a single, closed economy before turning to the open economy case.

3.1 Closed Economy Equilibrium

Labor is the only primary (non-produced) factor of production, and production requires labor and produced, intermediate goods as inputs. There are two sectors in the economy, tradable sector (intermediate goods) and nontradable sector (final goods). Formally, I assume that nontradable goods are continuum goods indexed by $v \in [0,1]$ and tradable goods are indexed by $u \in [0,1]$. A representative agent consumes a continuum of final consumption goods in quantities $q_f(v)$, deriving utility

$$U = \left[\int_0^1 q_f(v)^{\frac{\varepsilon-1}{\varepsilon}} dv \right]^{\frac{\varepsilon}{\varepsilon-1}}$$

with $\varepsilon > 0$.

A continuum of intermediate goods are used to produce a *composite intermediate good* Q via a CES production function with $\sigma > 0$,[23]

$$Q = \left[\int_0^1 q(u)^{1-1/\sigma} du \right]^{\sigma/(\sigma-1)}$$

Each intermediate tradable good is produced by a Cobb-Douglas production function using composite aggregate intermediate good and labor. Let $s(u)$ be the labor used to produce a given tradable $q(u)$ and let $Q_m(u)$ be the level of the composite aggregate. The production technology for individual intermediate good $q(u)$ is assumed to be

$$q(u) = x(u)^{-\theta} s(u)^{\beta} Q_m(u)^{1-\beta}. \tag{3.1}$$

where β is the labor share. Total factor productivity (TFP) levels are reflected by $x(u)^{-\theta}$ and vary across goods u. As in Eaton and Kortum (2002) and Alvarez and Lucas (2007), the individual $x(u)$

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[23] It is also called a Spence-Dixit-Stiglitz (SDS) aggregate.

(“costs” variable, i.e., the inverses of TFP) are random variables, independent across goods, with a common density g. Note that a low x-value means a high productivity level. Since intermediate goods differ only in their costs $x(u)$, and all goods $q(u)$ enter symmetrically in the aggregate, thus, as in Alvarez and Lucas (2007), I relabel intermediate good u by its cost draw, $x > 0$, and rewrite the aggregate Q in the form

$$Q = \left[\int_0^\infty q(x)^{1-1/\sigma} g(x) dx \right]^{\sigma/(\sigma-1)} \tag{3.2}$$

where $q(x)$ is production of individual tradable good x. Assume that the density g is exponential with parameter λ where λ is the stock of knowledge or technology state parameter: $x \sim exp(\lambda)$.[24] For each individual good u, there are two types of technologies (exclusive and diffusive technology) which can be used to produce u. The buyers pick the lowest cost from these two independent productivity draws. Therefore, as mentioned in section 2, $x = \min\{x^E, x^D\}$, where x^E and x^D are assumed to be independent. Also assume that $x^E \sim exp(\lambda^E)$ and $x^D \sim exp(\lambda^D)$. Then $\lambda = \lambda^E + \lambda^D$ by the properties of exponential distribution.[25] Hence, in a closed economy, differentiating between two types of technology does not change the equilibrium, and the only difference is that the current state of technology λ has two components: λ^E and λ^D. When diffusive knowledge does not exist (i.e., $\lambda = \lambda^E$), the model is going back to Alvarez and Lucas (2007).[26] However, this distinction will change the open economy equilibrium in section 3.2.

Rewriting equation (3.2) with density function of exponential distribution yields

$$Q = \left[\lambda \int_0^\infty e^{-\lambda x} q(x)^{1-1/\sigma} dx \right]^{\sigma/(\sigma-1)} \tag{3.3}$$

where λ is the parameter of the exponential distribution from which the productivity draw is realized. Then restate the production function of the individual tradable good as

$$q(x) = x^{-\theta} s(x)^\beta Q_m(x)^{1-\beta}. \tag{3.4}$$

Similar to tradable goods, nontradable goods are produced by a Cobb-Douglas function of Q_f composite intermediate good and the labor input s_f with labor share α. Nontradable goods are assumed to have the same productivity distribution with tradable goods. The cost parameter

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[24] $Pr[X \leq x] = 1 - e^{-\lambda x}$. The random variables $x^{-\theta}$ then have a Frechet distribution.

[25] The stock of knowledge is the sum of exclusive knowledge and diffusive knowledge. Also see footnote 14.

[26] In Alvarez and Lucas (2007) and Eaton and Kortum (2002), all technology is implicitly assumed to be exclusive to its home country which is a special case in the present model, i.e., $\lambda^D = 0$, $\lambda = \lambda^E$

associated with nontradable goods is denoted by $\tilde{x}(v)$ where $\tilde{x} \sim exp(\lambda)$. The production function of the final goods is

$$q_f(\tilde{x}) = \tilde{x}^{-\theta} s_f(\tilde{x})^{\alpha} Q_f(\tilde{x})^{1-\alpha}. \tag{3.5}$$

In per capita terms, the resource constraints imply that

$$\lambda \int_0^{\infty} e^{-\lambda\tilde{x}} s_f(\tilde{x}) d\tilde{x} + \lambda \int_0^{\infty} e^{-\lambda x} s(x) dx = 1, \tag{3.6}$$

$$Q_m + Q_f = Q, \tag{3.7}$$

where

$$Q_m = \lambda \int_0^{\infty} e^{-\lambda x} Q_m(x) dx, \quad Q_f = \lambda \int_0^{\infty} e^{-\lambda\tilde{x}} Q_f(\tilde{x}) d\tilde{x}. \tag{3.8}$$

Let the unit price of individual tradables be $p(x)$. Denote the unit price of aggregate composite tradable goods by p_m. Finally, let the unit price of nontradable goods be $p_f(\tilde{x})$. In the equilibrium,

$$p(x) = x^{\theta} B w^{\beta} p_m^{1-\beta} \tag{3.9}$$

where $B = \beta^{-\beta}(1-\beta)^{\beta-1}$. The unit cost of input bundle for tradable good is $c^T = Bw^{\beta} p_m^{1-\beta}$ and the unit price of tradable good is $x^{\theta} c^T$. The unit price p of the nontradable good is

$$p_f(\tilde{x}) = \tilde{x}^{\theta} A w^{\alpha} p_m^{1-\alpha} \tag{3.10}$$

where $A = \alpha^{-\alpha}(1-\alpha)^{\alpha-1}$ and the unit cost of the input bundle for nontradable good is $c^{NT} = Aw^{\alpha} p_m^{1-\alpha}$. The unit price of nontradable good is $\tilde{x}^{\theta} c^{NT}$.[27] The unit price of aggregate intermediate is

$$p_m = (CB)^{1/\beta} \lambda^{-\theta/\beta} w. \tag{3.11}$$

where C is a constant.

In this closed Ricardian model, I first solve for the equilibrium prices p_f, p_m, and $p(x)$ in terms of the wage w. Using these prices, I calculate equilibrium quantities. Figure 1 illustrates the cost

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[27] This is because of the same productivity draw for nontradable goods production and for tradable goods. Hence, technology diffusion will have direct impact on the price of consumption goods. This will amplify the effect of technology diffusion in nontradable sector. Rodríguez-Clare (2007) and Ramondo and Rodríguez-Clare (2008) have the similar set-up to address global technology diffusion and multinational production problem. If I assume that there is no random shock of productivity for production of nontradable goods as in Alvarez and Lucas (2007) and all productivity shocks occur in tradable sector, it turns out to give very low welfare impact of technology diffusion.

structure in closed economy. The detailed derivation of closed economy equilibrium is contained in Appendix A.

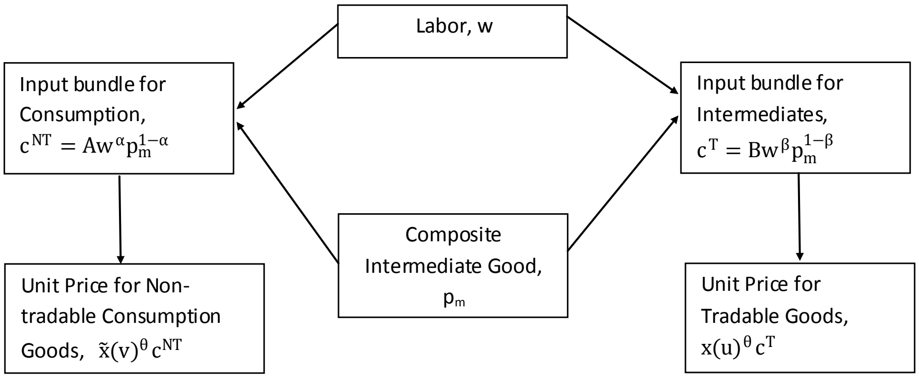

Figure 1: The cost structure in closed economy

3.2 General Equilibrium

Consider an equilibrium in a world of I countries, all with the structure described in section 3.1, in which merchandise trade is balanced. Note that differentiating between exclusive and diffusive technology does not change the equilibrium in closed economy, but does impact the equilibrium in open economy case.

A new notation for the commodity space is needed. Assume that these cost draws are independent across countries and across two types of technologies: $x_i^E \sim exp(\lambda_i^E)$ and $x_i^D \sim exp(\lambda_i^D)$ for country i. Let x^E and x^D be two vectors: $x^E = (x_1^E, x_2^E, ..., x_I^E)$, $x^D = (x_1^D, x_2^D, ..., x_I^D)$. Use $q_n(x^E, x^D)$ for the consumption of tradable good (x^E, x^D) in country n, and Q_n for consumption of the aggregates in country n. Let $p_n(x^E, x^D)$ be the prices paid for tradable good (x^E, x^D) by producers in country n. Let p_{mn} be the price in country n for a unit of the aggregate.

Analogous to Section 2, for tradable goods, all producers in country n buy at the same, lowest price:

$$\begin{aligned} p_n(x^E, x^D) &= \min\{\min_i (x_i^E)^{\theta} c_i^T / k_{ni}, \min_{i,m} (x_i^D)^{\theta} c_{mi}^T / k_{nm}\} \\ &= \min\left\{\min_i (x_i^E)^{\theta} \frac{c_i^T}{k_{ni}}, \min_{i,m} (x_i^D)^{\theta} \frac{c_m^T}{b_{mi} k_{nm}}\right\} \end{aligned} \tag{3.12}$$

where $c_i^T = Bw_i^{\beta} p_{mi}^{1-\beta}$, $i = 1, ..., I$. The first term on the RHS minimizes over all possible ways in which country n can procure the tradable goods conditional on using exclusive technology, which precludes diffusive technology and implies importing goods from the country where the exclusive technology originates. The second term on the RHS minimizes over all possible ways in which country n can procure the tradable goods conditional on using diffusive technology, which allows for technology diffusion from i to the production country (intermediary country) m for all possible $\{i, m\}$ combinations.

Then I derive an expression for the price index of tradable aggregates p_{mn},

$$\begin{aligned} p_{mn}(w) &= CB \left(\sum_{i=1}^{I} \psi_{ni} \right)^{-\theta} \\ &\equiv (CB) \left(\sum_{i=1}^{I} \left(\left(\frac{w_i^{\beta} p_{mi}(w)^{1-\beta}}{k_{ni}} \right)^{-1/\theta} \lambda_i^E + \min_m \left(\frac{w_m^{\beta} p_{mm}(w)^{1-\beta}}{b_{mi} k_{nm}} \right)^{-1/\theta} \lambda_i^D \right) \right)^{-\theta} \end{aligned} \tag{3.13}$$

where $i, m = 1, ..., I$, and C is the constant defined in Appendix A.

Following Alvarez and Lucas (2007), I view (3.13) as a system of I equations in the prices $p_m = (p_{m1}, p_{m2}, ..., p_{mI})$, to be solved for p_m as a function of the wage vector w. This price index expression can be compared with the price formula (7) and (9) in Eaton and Kortum (2002) and the price formula (3.8) in Alvarez and Lucas (2007). The difference is the second term in RHS due to technology diffusion. Without diffusion, letting all technology be exclusive ($\lambda_i^E = \lambda_i$, $i = 1, 2, ..., I$), the model is collapsed to Alvarez and Lucas (2007). Note that now with diffusion, both trade costs k and diffusion barriers b impact the price index.

The analysis in Section 2.2 to compute total imports of goods by country n from country i is still valid except for three changes. First, the value of intermediate goods produced with exclusive technology in country i that are exported to country n is no longer $\tau_{ni}^E X_n$ but $\tau_{ni}^E X_n^T$, where X_n^T is total spending on intermediates by country n. Similarly, total imports by country n from country i of intermediate goods produced with diffusive technology are now $\sum_j \tau_{nij}^D X_n^T$. Then I have total imports of goods by country n from $i \neq n$

$$M_{ni} = \tau_{ni}^E X_n^T + \sum_j \tau_{nij}^D X_n^T. \tag{3.14}$$

Hence, imports of goods are comprised of two parts: the tradable goods produced by exclusive technology captured by the first term and the tradable goods produced by diffusive technology captured by the second term.

Next I calculate the tradables expenditure shares for each country n: the fraction D_{ni} of country n's total per capita spending $p_{mn}Q_n$ on tradables that is spent on goods from country i. Since $X_n^T = p_{mn}Q_nL_n$, from (3.14) and (3.13) I have the expression of bilateral merchandise import share in total spending on tradable goods D_{ni}

$$\begin{aligned} D_{ni} &= \tau_{ni}^E + \sum_j \tau_{nij}^D \\ &= (CB)^{-1/\theta} \left\{ \left(\frac{w_i^\beta p_{mi}(w)^{1-\beta}}{p_{mn}(w)k_{ni}} \right)^{-1/\theta} \lambda_i^E + \sum_j \left[y_{nij}^D \min_m \left(\frac{w_m^\beta p_{mm}(w)^{1-\beta}}{p_{mn}(w)b_{mj}k_{nm}} \right)^{-1/\theta} \lambda_j^D \right] \right\} \end{aligned} \tag{3.15}$$

Note that $\sum_i D_{ni} = \frac{\sum_i \tau_{ni}^E + \sum_i \sum_j y_{nij}^D \tau_{nj}^D}{\tau_n} = 1$ because $\sum_i y_{nij}^D = 1$. Also note that "complementary slackness" conditions mentioned in Section 2.2 still hold. Equation (3.15) can be compared with the import share formula (3.10) in Alvarez and Lucas (2007) and the difference is the second term in RHS due to technology diffusion. When all technology is exclusive technology (i.e., $\lambda_i^E = \lambda_i$), (3.15) is exactly the same formula with the one in Alvarez and Lucas (2007).

Next, I calculate the total value associated with inward technology diffusion M_{ni}^D from country i to country n. Compared to the simple model with only tradable sector, now M_{ni}^D is comprised of two parts: inward technology diffusion used in tradable goods, $M_{ni}^{D,T}$, plus the corresponding value for consumption goods, $M_{ni}^{D,NT}$,

$$M_{ni}^D = M_{ni}^{D,T} + M_{ni}^{D,NT} = \sum_j \tau_{jni}^D X_j^T + \frac{\varphi_{ni}^D}{\varphi_n} X_n \tag{3.16}$$

and $\varphi_n \equiv \varphi_{nn}^E + \sum_i \varphi_{ni}^D$, where $\varphi_{nn}^E = (c_n^{NT})^{-1/\theta}\lambda_n^E$ reflects the impact of exclusive technology on nontradable goods, and $\varphi_{ni}^D = (c_{ni}^{NT})^{-1/\theta}\lambda_i^D$ reflects the impact of diffusive technology on nontradable goods. The second term in φ_n suggests that country n can use diffusive technology from all possible technology source country i in its nontradable sector. This changes the price of consumption goods.

Total spending on final goods by country n is $X_n = w_nL_n$. It can be shown that total spending on tradable intermediate goods is $X_n^T = \left(\frac{1-\alpha}{\beta}\right) X_n$, derived from the share formula (A.15) and

(A.18) in Appendix A. Thus total merchandise imports by country n from i are

$$M_{ni} = \left(\frac{1-\alpha}{\beta}\right)\left(\tau_{ni}^{E} + \sum_{j}\tau_{nij}^{D}\right) w_n L_n \tag{3.17}$$

Imposing trade balance condition yields

$$\sum_{i \neq n} M_{ni} = \sum_{i \neq n} M_{in} \tag{3.18}$$

Aggregate imports for country n are simply $M_n = \sum_{i \neq n} M_{ni}$. Trade share for country n is $V_n = M_n/(w_n L_n)$ or $V_n = (1-D_{nn})(1-\alpha)/\beta$. Diffusion share for country n is $V_n^D = M_n^D/(w_n L_n) = (\sum_{i \neq n} M_{ni}^D)/(w_n L_n)$. The bilateral diffusion share in country n's total spending is simply $M_{ni}^D/(w_n L_n)$.

I can also rewrite the above trade balance condition in more detail. Under the trade balance assumption, the dollar payments for tradables flowing into n from the rest of the world must equal the payments flowing out of n to the rest of the world. Firms in n spend a total of $X_n^T = p_{mn} Q_n L_n$ dollars on tradables. The amount $p_{mn} Q_n L_n \sum_{i=1}^{I} D_{ni} = p_{mn} Q_n L_n$ reaches sellers in all countries. Buyers in country i spend a total of $p_{mi} Q_i L_i D_{in}$ dollars for tradables from n. Thus trade balance requires

$$p_{mn} Q_n L_n = \sum_{i=1}^{I} p_{mi} Q_i L_i D_{in}. \tag{3.19}$$

Solving the equilibrium involves finding the zeros of a system $Z(w)$:

$$Z_n(w) = \frac{1}{w_n}\left[\sum_{i=1}^{I} L_i w_i (1-\alpha) D_{in}(w) - L_n w_n (1-\alpha)\right] \tag{3.20}$$

As in the closed economy analysis of Section 3.1, the full set of equilibrium prices and quantities are determined once equilibrium wages are known.[28] Once the prices are determined, the equilibrium quantities can be derived as in the closed economy analysis. The detailed derivation of equilibrium is contained in Appendix B.

A ***competitive equilibrium*** *is characterized by a wage vector* $w \in \mathbf{R}_{++}^{n}$ *such that* $Z_n(w) = 0$ *for* $n = 1, ..., I$*, where, the price functions for tradable goods* $p_{mn}(w)$ *satisfy (3.13), the price functions for nontradable goods* p_{fn} *satisfy* $p_{fn} = C\varphi_n^{-\theta}$*, the bilateral import share functions* $D_{ni}(w)$ *satisfy (3.15), the goods imports from country* i *to* n *satisfy (3.17), and the technology diffusion from*

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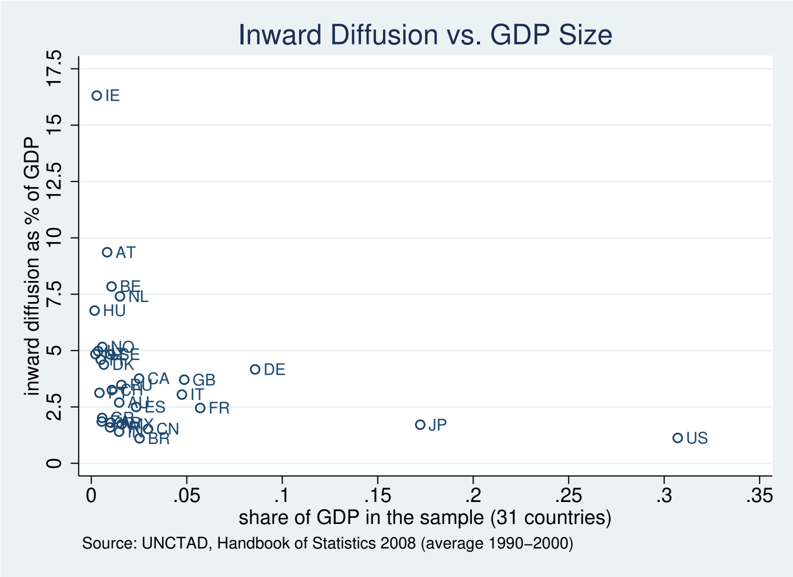
[28] Alvarez and Lucas (2007) provide a proof that there exists a unique solution to (3.15), given tradable goods prices.

country i to n satisfies (3.16).

4 Benchmark

I calibrate the model's parameters using data on the value of merchandise trade imports, the value of payments associated with inward technology diffusion (represented by the payments associated with imports of international trade in royalties, license fees, and information intensive services), GDP size (as percentage of world GDP), and real GDP per capita for a sample of 31 countries. The calibrated model is used as a benchmark to perform some counterfactual exercises to quantitatively analyze the welfare gains from reducing trade costs and diffusion barriers.


Inward Diffusion vs. GDP Size

Source: UNCTAD, Handbook of Statistics 2008 (average 1990–2000)

Figure 2: The magnitude of technology diffusion as % of GDP across countries

4.1 Data Description

The sample is comprised of 31 countries, which include nineteen OECD countries plus 12 other countries. The nineteen OECD countries are the U.S., Japan, Germany, France, United Kingdom, Italy, Canada, Spain, Australia, Netherlands, Belgium/Luxemburg, Sweden, Austria, Denmark, Norway, Finland, Greece, Portugal, and New Zealand.[29] The other 12 countries are China, Brazil, Mexico, India, Russia, Argentina, Switzerland, Turkey, South Africa, Israel, Ireland and Hungary.

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[29] These 19 OECD countries are also the ones considered by Eaton and Kortum (2002) and Ramondo and Rodríguez-Clare (2009).

These countries were selected since they are all significant as percentage of world GDP and they all have large aggregate knowledge stock.[30] Also, those 31 countries are those which report data on the trade in royalties and license fees plus information intensive services, compared to the sample in Alvarez and Lucas (2007).[31]

All data are averages over 1990-2000 (see Appendix C). I use merchandise trade imports as percentage of GDP from UNCTAD as the empirical counterpart for the trade share V_i for country i in the model. Data on international technology diffusion are constructed based on the payments data of royalties and license fees trade, trade in computer and information services, and trade in communications services from UNCTAD.[32] The value of inward technology diffusion as percentage of GDP is the empirical counterpart for inward diffusion share V_i^D for country i in the model.[33] Figure 2 illustrates that inward technology diffusion as a percentage of GDP is as high as 16.3% in Ireland and is on average 4% in the sample.[34] The size of GDP as a percentage of world GDP from World Development Indicators (WDI) is the target of $L_i w_i$ (normalized) for country i in the model.[35] Another moment condition I used is the real GDP per capita (PPP adjusted), from Penn World Table. In the model, this variable is the ratio of $(w_i L_i)/p_{fi}$ to population in country i and population data are obtained from UNCTAD.[36] Variable L_i is adjusted employment size rather than real population. This variable captures the total number of "equipped-efficiency" units available for production in the present model without capital; thus, L_i as employment must be adjusted to account for human and physical capital available per worker (Ramondo and Rodríguez-Clare, 2009). Following Alvarez and Lucas (2007), I calibrate L_i with λ_i.[37]

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[30] I use different indicators of knowledge stock, for example, the total number of patents in the country, the total number of patent citations the country receives, and the aggregate royalties and license fees trade (i.e., the sum of the inward and outward royalties and license fees).

[31] I try to compare my results with Alvarez and Lucas (2007) which contains 60 countries. Among them, those 31 countries report the data on international technology diffusion. Among them, only some OCED countries report bilateral technology diffusion flows. While most developing countries and emerging markets do not report bilateral technology diffusion flows with their trading partners. Therefore, in the calibration part I will focus on country-specific diffusion rather than bilateral diffusion.

[32] I also include trade in personal services (e.g. fees for training/provision of courses overseas, teachers abroad, etc.) in technology diffusion since flows of knowledge involve talent migration and human capital training. But the magnitude of this part is small.

[33] The diffusion share in the model and diffusion share in the data are defined slightly differently. V_i^D in the model is the value of goods produced by diffusive technologies from abroad. V_i^D in the data is the value associated with inward knowledge movement, i.e., import of royalties and license fees plus information intensive services. Using this data potentially underestimates the real diffusion, since payments of royalties and license fees plus information intensive services usually capture part of the final value of goods produced by diffusive technologies. To check the potential impact of this, I examine an alternative calibration in the robustness checks (see Section 5 and Table 15) and find that the main results are not sensitive.

[34] This magnitude is even larger than R&D expenditures as percentage of GDP. For example, during the same period, all OECD countries spent around 2.1% of GDP on R&D expenditures.

[35] GDP in current dollars (Data source: WDI 2009 online database, average 1990-2000).

[36] Data source: UNCTAD Handbook of Statistics (2008).

[37] Alvarez and Lucas (2007) pursue two approaches to calibrating λ and L. First, they assume that λ is proportional

4.2 Calibration Procedure

My procedure is to calibrate some of the model's parameters: knowledge stock (technology state) parameter λ_i, country-specific trade costs k_i, country-specific diffusion barriers b_i, and the share of diffusive knowledge in the overall knowledge stock δ_i^D.[38] I use the data on trade share, diffusion share, real GDP per capita, and GDP as a percentage of world GDP for 31 countries. To reduce the number of parameters to calibrate, I assume that the proportion of diffusive knowledge is the same across countries, $\lambda_i^E + \lambda_i^D = \lambda_i$, $\lambda_i^D/\lambda_i = \delta^D$.

The resulting set of parameters to calibrate is

$$\Upsilon = \left\{ \{\lambda_i\}_{i=1}^{I}, \delta^D, \{k_i\}_{i=1}^{I}, \{b_i\}_{i=1}^{I}, \alpha, \beta, \theta \right\}.$$

I set the labor share in the tradable sector, β, to 0.5, and the labor share in the final sector, α, to 0.75, as in Alvarez and Lucas (2007). I select a value of 0.15 for parameter θ, which is the value used in Alvarez and Lucas (2007) as a baseline. This is the preferred value based on the following information. The parameter θ reflects the variability of productivity across countries. The selected baseline value of θ lies in the middle of empirical estimates. Eaton and Kortum (2002) estimate θ using bilateral trade data as well as prices of individual goods. Their estimates for θ are in the range 0.08-0.28, and their preferred value is 0.12. Anderson and van Wincoop (2004) conclude that a reasonable range for the estimates of the Armington substitution elasticity is $[5, 10]$, which corresponds to $\theta \in [0.11, 0.25]$.[39] Based on these findings, as in Alvarez and Lucas (2007), I choose $\theta = 0.15$ as the preferred value. See Table 1 for the definition of parameters in the model and how to set their values.

My calibration procedure is as follows. First, given α, β, θ, the initial guess of other parameters in Υ, and the vector of country GDP sizes as percentage of world GDP, I compute the model's equilibrium, and generate a simulated data set for the following variables: trade shares, diffusion shares, the real GDP per capita, and the country's GDP share in the world. The algorithm used

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to L and calibrate both to match a country's share of nominal world GDP. The second approach uses relative price data to calibrate λ and L separately. They found that both approaches produce similar results. In this paper, I use the first approach as in Alvarez and Lucas (2007) to match countries size in world GDP distribution.

[38] To estimate trade costs and diffusion barriers, I do two steps. First, I calibrate the simplest version of the model under the assumption of uniform trade cost k and diffusion barrier b. The purpose of the first step is finding some reasonable intervals for the final optimal values to save the computation time. Second, I calibrate country-specific trade costs and diffusion barriers.

[39] This is because the connection between these two parameterizations is $\theta = 1/(\sigma - 1)$, based on the bilateral gravity formula.

Table 1: Parameters

Parameter	Definition	Value
α	labor share (non-tradable)	0.75 (Alvarez and Lucas, 2007)
β	labor share (tradable)	0.5 (Alvarez and Lucas, 2007)
θ	variability of productivity draws	0.12 (Eaton and Kortum, 2002) 0.15 (Alvarez and Lucas, 2007)
δ_i^D	share of diffusive technology	assume $\delta_i^D = \delta^D$ recovered from real GDP per capita
λ_i	technology state (total stock of knowledge)	$\lambda_i \sim L_i$
L_i	adjusted employment (size)	recovered from GDP share in the world
k_{ni}	trade costs b/w n and i	recovered from trade share
b_{ni}	diffusion barriers b/w n and i	recovered from diffusion share

to compute the model's equilibrium extends the one in Alvarez and Lucas (2007) using contract mapping to find a fixed point of wages w that solves for the vector of price index $p_m(w)$.[40] The calibration searches for: (1) the technology state parameters (also the stock of knowledge) $\{\lambda_{i=1}^I\}$ recovered from the GDP share in the world such that the absolute difference of GDP share between the model prediction and the real data is minimized, as in Alvarez and Lucas (2007);[41] (2) the share of diffusive knowledge in overall knowledge stock δ^D, the trade costs k_i and the diffusion barriers b_i such that the sum of the square difference of real GDP per capita ($gdpp_i$), trade shares (V_i) and diffusion shares (V_i^D) for all countries between the model and the data is minimized,

$$\sum_{i=1}^{I}\left(\widetilde{gdpp_i}^{data}-\widetilde{gdpp_i}^{model}\right)^2+\sum_{i=1}^{I}\left(\widetilde{V}_i^{data}-\widetilde{V}_i^{model}\right)^2+\sum_{i=1}^{I}\left(\widetilde{V_i^D}^{data}-\widetilde{V_i^D}^{model}\right)^2.$$

In each simulation, I recover technology state parameters $\{\lambda_{i=1}^I\}$ from the country's GDP size as percentage in the world, and use three other moment conditions (real GDP per capita, trade share and diffusion share for each country) to pin down country-specific trade costs k_i, country-specific diffusion barriers b_i, and the share of diffusive knowledge in overall knowledge stock δ^D. It is worth noting that the three moment conditions are jointly determined by these three parameters. The whole nonlinear system is comprised of 93(=31×3) nonlinear equations and 63(=31×2+1) unknowns.

A measure of the explanatory power of the model for trade shares R_V^2, diffusion shares $R_{V^D}^2$,

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[40] The algorithm is described below. First, given the vector of wages w, there exists a function $p_m(w)$ that solves for the vector of price index p_m. Second, there is a mapping $w' = T(w; y^T)$ whose fixed point, $w = F(y^D)$, gives the equilibrium wages given a 3-dimension matrix y_{nij}^D. This 3-dimension matrix y^D captures the relationship between the technology source country, the production country as intermediary, and the destination consumption country in tradable goods sector. Then the final step is to solve for the whole equilibrium.

[41] For simplicity, I follow Alvarez and Lucas (2007) to assume that $\lambda_i \sim L_i$.

country's GDP size, R^2_{GDP} and real GDP per capita R^2_{gdpp}, respectively, is given by:

$$R^2_H = 1 - \frac{\sum_{i=1}^{I}\left(\widetilde{H}_i^{data} - \widetilde{H}_i^{model}\right)^2}{\sum_{i=1}^{I}\left(\widetilde{H}_i^{data}\right)^2} \tag{4.1}$$

where $H = V, V^D, GDP, gdpp$. I will report both the explanatory power and the correlation between the real data and the model generated results in Section 4.3.

The chosen moments are informative about the model's parameters. Intuitively, the sources of identification are as follows. First, λ is the total stock of knowledge, which is believed to be proportional to the size of an economy, as in Alvarez and Lucas (2007). Therefore, I use GDP size as a percentage of world GDP to pinpoint λ. Second, diffusion barriers have a greater effect on diffusion shares, while trade costs have a greater effect on trade shares, even though the trade shares and the diffusion shares are jointly determined by both trade costs and diffusion barriers. Third, the share of diffusive knowledge is related to real GDP per capita. Increasing the share of diffusive knowledge δ^D effectively increases real GDP per capita, and changing the value of real GDP per capita leads to a change in the share of diffusive knowledge. Hence, I use real GDP per capita as a moment condition to identify diffusive knowledge share. In calibration, the last three moment conditions are jointly used to identify diffusion barriers, trade costs, and the share of diffusive knowledge.

4.3 Benchmark Results

Table 2 reports the calibrated parameters for the benchmark. The calibrated trade cost k_i is, on average, 0.54, which is equivalent to adding 85% tariff or shipping costs. This estimate is broadly consistent with the value of trade costs used in the existing literature. Alvarez and Lucas (2007) do not calibrate the value of trade costs and used $k = 0.75$, applied symmetrically to country pairs i, j with $i \neq j$. The value 0.75 does not include the effect of tariffs. Considering tariffs, the real value of k is lower than 0.75. Furthermore, Alvarez and Lucas (2007) also note that other statistical evidence can support k values (trade costs) as low as 0.65. Anderson and van Wincoop (2004) report that for a representative developed country, trade barriers fall in a range between 40–80%, depending on the approach and elasticity of substitution. Waugh (2010) finds even larger trade costs: the median trade cost for OECD countries is equivalent to a 90% tariff, which is equivalent to the value of trade costs k of 0.53. My estimate for trade costs is within these reasonable ranges.

Table 2: Parameters (31 countries with country-specific k_i and b_i)

Parameterized Parameter	Definition	Value	Previous literature
α	labor share (non-tradable)	0.75	0.75 (Alvarez and Lucas, 2007)
β	labor share (tradable)	0.5	0.5 (Alvarez and Lucas, 2007)
θ	variability of productivity	0.15	0.12-0.28 (Eaton and Kortum, 2002)
Calibrated Parameter	**Definition**	**Value**	**Previous literature**
δ^D	share of diffusive technology	0.14	N/A
k_i	trade cost (average 31 countries)	0.54	0.75 plus tariff (Alvarez and Lucas, 2007) 0.65 from statistical evidence
b_i	diffusion barriers (average 31 countries)	0.45	N/A

The calibrated value of average diffusion barriers is $b = 0.45$. This implies that the barriers to technology diffusion among the sample countries are larger than the trade costs. This result is quite interesting because it contradicts some general conjectures by the public that knowledge flows might take more advantage of communication technology and that it might therefore be the case that, even though knowledge flows entail barriers, those barriers are lower than the barriers to merchandise trade flows. However, this paper provides an opposite answer. It specifically investigates the diffusion barriers in which technology diffusion occurs through market transactions, which can be viewed as trade in knowledge in a general sense. The calibrated diffusion barriers are larger than merchandise trade costs, which means that merchandise trade is less costly compared to trade in knowledge.

The calibrated proportion of diffusive knowledge in overall knowledge stock is 0.14, which means that roughly 86% of knowledge stock is exclusive to its home country and that only a small proportion of knowledge is currently used by foreign countries through market transactions of diffusion. This large share of exclusive technology is consistent with the conventional assumption in the literature of Ricardian trade, which implicitly assumes that all technology is exclusive (e.g., Alvarez and Lucas, 2007; Eaton and Kortum, 2002).

Table 3: Goodness of Fit: Calibrated Model

Model's "Explanatory power":	
merchandise trade shares	0.97
technology diffusion shares	1.00
real GDP per capita	0.96
GDP size	1.00
Correlations between model and data:	
merchandise trade shares	0.92
technology diffusion shares	1.00
real GDP per capita	0.97
GDP size	1.00

Table 3 reports the model's explanatory power and the correlation between the model and the data. The calibrated model does a very good job in matching GDP size and technology diffusion share as percentage of GDP, and the fitness for merchandise trade share and real GDP capita is also above 95% in terms of explanatory power. In a model without technology diffusion, the correlation coefficient between the model generated merchandise trade and the data is 0.59, as in Alvarez and Lucas (2007). My model generates the correlation as high as 0.92 for merchandise trade share (as a percentage of a country's GDP). My model replicates most countries very well: if Belgium and Luxembourg are excluded, the explanatory power for merchandise trade share increases to 0.97, and the correlation between the model and the data becomes 0.93.[42] Figure 3-4 also report the fitness of data and the model. In Figure 3, the left panel compares countries' GDP sizes between the model and the data. If the model's GDP size is the same as that of the data, then the ordered pairs would map out a 45^o line. Figure 3 shows that the ordered pairs of GDP size lay on the 45^o line. The model also replicates real GDP per capita across countries fairly well. For example, the model predicts that Finland has a real GDP per capita level that is 0.662 of the U.S. level. In the data, Finland has a real GDP per capita level that is 0.663 of the U.S. level.

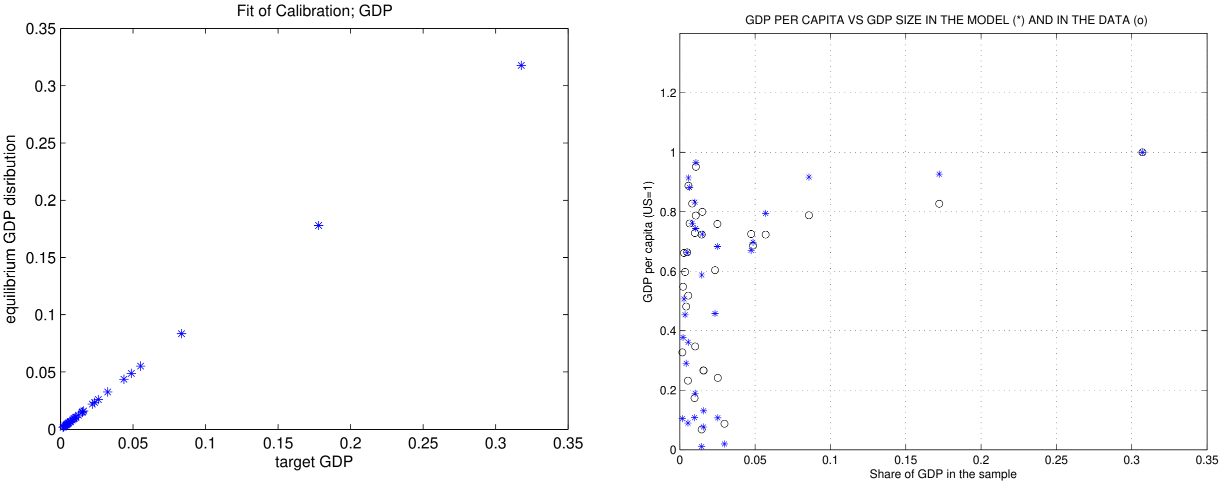

Figure 3: Country's GDP size and real GDP per capita (Model and Data).

Table 8 reports trade costs, diffusion barriers, GDP size, and technology parameters by country (see Appendix C). For most countries in the world, calibrated diffusion barriers are larger than merchandise trade costs. However, there are some exceptions; for example, Japan and Switzerland have smaller diffusion barriers than trade costs for goods. Japan usually faces larger trade costs compared to most other European and North American countries because it is isolated from other countries. At the same time, Japan is one of the largest technology producers in the world and has

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[42] Belgium and Luxembourg is an outlier which has merchandise trade share as high as 59%.

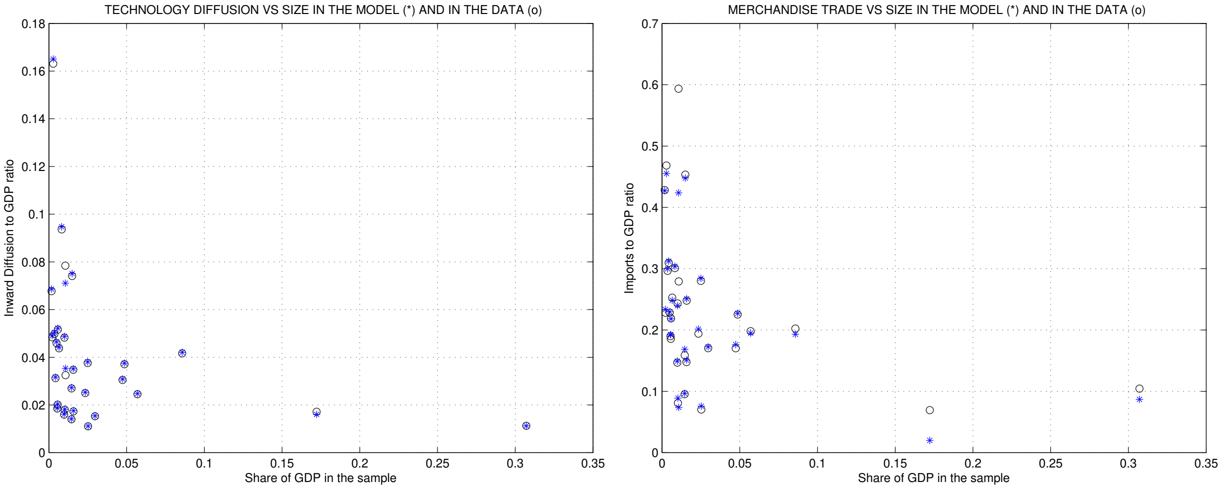

Figure 4: Merchandise trade and technology diffusion shares vs. GDP size (Model and Data).

relatively large knowledge stock. Switzerland is different from other European countries in terms of its distinct intellectual property law system, which helps its market transactions of technology diffusion. It is therefore unsurprising that Japan and Switzerland have smaller diffusion barriers than merchandise trade costs.

Furthermore, diffusion barriers show less variation across countries than do trade costs: the variance of trade costs (0.016) is almost four times that of diffusion barriers (0.004). This suggests that trade costs for goods are more asymmetric across countries while countries are facing more equalization in technology diffusion barriers. The potential reasons are as follows. Merchandise trade is more likely affected by physical trade barriers such as geographic ones, which include distance and borders. Such physical barriers are hard to diminish, and to some extent, they are inherent characteristics of a country. Conversely, even though physical distance and borders can also impede knowledge flows, technology diffusion might be more affected by institutional, cultural, and legal factors, for example, human capital levels and the legislation of intellectual property right. Such factors are amenable to change by policy instruments. My sample does not include many less developed countries; therefore, the differences between those factors across countries are not as large as the barriers to merchandise trade. Further exploration of different factors that could impede technology diffusion and the importance of each factor are outside the scope of this paper, and these issues are left for future research.

5 Counterfactual Exercises

In order to quantitatively examine the change in welfare gains and the cross-country distribution of GDP from reducing trade costs and diffusion barriers, I perform two counterfactual exercises based on the benchmark model. First, what would happen if trade costs and diffusion barriers were eliminated? I consider three cases: only removing diffusion barriers, only removing trade costs, and removing both trade costs and diffusion barriers. Second, what would happen if the world moved to autarky? I also consider three subcases here: only abolishing diffusion, only abolishing trade, and complete isolation (abolishing both trade and diffusion).

Welfare Gains

I use the two counterfactual exercises to analyze the change of welfare gains in terms of both consumption equivalence and real GDP per capita. Table 4 presents the change of consumption equivalence under different scenarios.[43] I find that the welfare boom from free diffusion (i.e., b goes to 1) is larger than that from free trade (i.e., k goes to 1). I use log change in percentage to denote the change of welfare. The consumption increment from removing diffusion barriers is, on average, 34%, which is larger than the average welfare increase from removing trade costs, 25%. Unsurprisingly, removing both trade costs and diffusion barriers present the largest welfare increase, which is, on average across countries, 60%. It is also interesting to examine the change from the current benchmark to autarky. Abolishing only merchandise trade (i.e., k goes to 0) leads to more welfare losses compared to abolishing diffusion alone (i.e., b goes to 0), and most of the welfare loss of moving to autarky (i.e., abolishing both trade and diffusion) is due to abolishing merchandise trade. This suggests that the world may have already exploited more benefits of merchandise trade cost reduction than from diffusion barrier reduction (i.e., from prohibitive trade costs or from prohibitive diffusion barriers to the benchmark), while in future, the potential gains from free diffusion are larger than from free trade (i.e., from the benchmark to free diffusion or to free trade). The implication of this finding is that greater investigation of policy instruments that may reduce diffusion barriers may be warranted. Table 9 reports the change in welfare gains by country (see Appendix C).

The welfare gains from free merchandise trade alone are consistent with those of Alvarez and Lucas (2007). For example, Alvarez and Lucas (2007) calculated the upper bounds of gains of moving from autarky to free trade in terms of consumption equivalence for the U.S., Japan, and

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[43] In the model, the consumption equivalence is equal to the real wage w/p_f.

Table 4: Welfare Gains (%)
(consumption equivalence)
$(log(con_1/con_0)) * 100$

From benchmark to:	Average 31 countries	Maximum among 31 countries
free trade and free diffusion $(k = 1, b = 1)$	59.55	113.58
only free trade in goods $(k = 1)$	25.28	37.92
only free technology diffusion $(b = 1)$	33.60	59.30
shutting down trade in goods $(k = 0)$	-5.18	-17.78
shutting down technology diffusion $(b = 0)$	-0.62	-2.67
shutting down both $(k = 0, b = 0)$	-5.80	-20.45

Denmark as 10%, 14%, and 38%, respectively. My results of gains of moving from autarky to free merchandise trade for these three countries are 10%, 15%, and 36%, respectively. When both diffusion and trade are permitted, the overall gains are larger: 15% for the U.S., 25% for Japan, and 77% for Denmark. Here, small countries benefit more than large countries do from both merchandise trade and technology diffusion because of the market size effect. Once trade costs or diffusion barriers are eliminated, countries enjoy the global market without friction. The result is that small countries can benefit from larger outside markets than they were able to previously, while big countries (e.g., the U.S., Japan) already have large domestic markets and thus benefit less from reducing trade costs or diffusion barriers. This market size effect occurs both in merchandise trade and technology diffusion. Therefore, when diffusion is included, a small country (e.g., Denmark) enjoys a larger welfare increase than do big countries (e.g., the U.S. and Japan).

The results can be also compared with the literature on gains from global technology diffusion without diffusion barriers. For example, Rodríguez-Clare (2007) calculated the overall gains from both trade and diffusion to be between 206% and 240% for a country with approximately 1% of the world's GDP. My results for overall gains from trade and diffusion for a similar country are around 69%-73%. The gains from diffusion in this paper are smaller than those of Rodríguez-Clare (2007) for two reasons. First, Rodríguez-Clare (2007) bases his work on the growth rate of a country, and no data associated with technology diffusion are directly used in that paper. I used market transaction data to directly quantify the gains from technology diffusion, resulting in their precise lower bound. Second, technology diffusion entails no trade costs or diffusion barriers in the literature. Therefore, gains from diffusion in this paper should be smaller than those based on Rodríguez-Clare (2007).

Table 5: Change of Real GDP Per Capita (%)

$(log(gdpp_1/gdpp_0)) * 100$

From benchmark to:	Average 31 countries	Maximum among 31 countries
free trade and free diffusion $(k = 1, b = 1)$	46.16	100.19
only free trade in goods $(k = 1)$	16.71	29.35
only free technology diffusion $(b = 1)$	28.79	54.50
shutting down trade in goods $(k = 0)$	-3.90	-16.66
shutting down technology diffusion $(b = 0)$	-0.52	-2.54
shutting down both $(k = 0, b = 0)$	-4.46	-19.20

Table 6: Dispersion of Real GDP Per Capita

Scenario	var[log(gdpp)]	$gdpp_{90}/gdpp_{10}$	Gini index
Benchmark	1.3943	10.2352	0.3564
free technology diffusion	1.3613	8.5727	0.3415
free trade in goods	1.3487	8.8042	0.3483

Another measure of welfare gains is real GDP per capita, reported in Table 5. The results are consistent with the consumption equivalence measure: the increase of real GDP per capita from free diffusion is larger than that from free trade, and abolishing trade leads to larger welfare losses than does abolishing diffusion. The change in real GDP per capita by country is reported in Appendix C (Table 8).

The nontradable sector plays a key role in the gains from diffusion. If there is no productivity shock in nontradable goods, the gains from free trade (average 25.30%) will be larger than those from free diffusion (average 0.04%), but the overall gains will be smaller than those of the benchmark. The reason is that diffusive technology has a limited effect on tradable goods due to the substitution effect between merchandise trade and technology diffusion in tradable goods. That is, obtaining foreign technology to produce goods locally decreases the incentive to import goods. Because technology diffusion substitutes for merchandise trade, diffusion of technology benefits a sector the goods of which are not tradable more than it does a sector the goods of which are tradable. If no productivity shocks occur in nontradable sectors, it shuts down substantial channel for the impact of technology diffusion. Table 10 reports the welfare comparison result from only allowing for productivity shocks in the tradable sector (see Appendix C).

Cross-country Distribution of GDP

I examine the change in cross-country distribution of GDP in terms of real GDP per capita. Free merchandise trade and free technology diffusion increase real GDP per capita by 5–30% and 4–55%, respectively. In both cases, the dispersion of real GDP per capita across countries is reduced. Table 6 provides some summary statistics: the variance of log real GDP per capita, the 90/10 percentile ratio, and the Gini index across countries. Except for the variance of log real GDP per capita, the summary statistics indicate that free diffusion contributes only slightly more to the reduction of dispersion of GDP across countries than does free trade. The Gini index of real GDP per capita across countries is decreased by 4% due to moving from the benchmark to free technology diffusion and by 2% due to moving from the benchmark to free merchandise trade. This is consistent with the first finding that free technology diffusion generates larger gains than does free merchandise trade. Table 11 in Appendix C presents the change of real GDP per capita by country. The market size effect also impacts the change of real GDP per capita. Table 11 shows that some small rich countries (e.g., Norway, Finland) benefit more than do relatively poor, big countries (e.g., China, India).

Impact of Diffusion on Trade Flows

I examine the change of trade volume due to the change of diffusion barriers to investigate the impact of diffusion on trade flows. Table 12 in Appendix C presents the trade shares by country under different scenarios. By only removing the diffusion barriers, the trade shares slightly increase for all countries. Removing trade costs substantially increases trade shares. Finally, by removing both trade costs and diffusion barriers, trade shares reach their highest levels. The underlying mechanism is that free diffusion makes countries more likely obtain higher productivity draws from abroad through diffusion. In an asymmetric world, this encourages countries to be more specialized in production, and many countries will serve as intermediaries that export goods produced by foreign technology. Therefore, diffusion improves countries' potential ability to export goods to global markets. This is the complementarity effect, resulting in trade shares increasing after the removal of diffusion barriers.

This result is different from the analysis in Section 2 under symmetry because no intermediary countries exist in a symmetric world; therefore, only the substitution effect exists. This means that for tradable goods, if a country obtains more foreign technology through diffusion to produce goods locally, its incentive to import those goods decreases. My quantitative result suggests that in an asymmetric world, the substitution effect is dominated by the complementarity effect. This implies that removing diffusion barriers has "spillover" effects on merchandise trade, which supports the first two findings about the change in welfare and in real GDP per capita due to the removal of trade costs and diffusion barriers. In summary, free diffusion has greater welfare impact and contributes more to reducing the dispersion of real GDP per capita than does free merchandise trade.

Robustness

One potential issue is that the diffusive technology share δ^D might depend on diffusion barriers, and therefore should not be viewed as fixed in the experiments. The reason is that reducing diffusion barriers potentially makes diffusion more likely across national borders, and increases diffusive technology share. Then the effect of free diffusion might be magnified. If so, the previous results for the effect of removing the diffusion barriers would be the lower bound of the real effect of free diffusion. In that case, the welfare effect of free diffusion is downward biased. This share of diffusive technology is also related to extensive margin in technology market. It is interesting to compare the extensive margin (how much technology at aggregate level is diffused) and the intensive margin (how much technology diffusion each firm obtains). The task is promising and challenging where more technology diffusion data at firm level are needed.

To alleviate the δ^D problem as well as to check the sensitivity of calibration results, I recalibrate the model using different values of δ^D (see Table 13).[44] The value for trade costs is stable, and does not change much according to different values of diffusive technology share δ^D. The value of diffusion barriers b is decreasing when δ^D goes to 1. This implies that if more technology is diffusive, in order to fit the current world, higher diffusion barriers are necessary. In the extreme case (see Table 14), when the share of diffusive technology reaches closer to 1, the value of diffusion barriers is around 0.13. This gives out the average welfare gains from removing diffusion barriers as 34.8%, just a bit larger than the average gains in the benchmark 33.6% (see Table 4).[45] But it increases the maximum welfare increment to 82.1%, compared to the previous value 59.3% in Table 4. Therefore, it is safely to say that the average welfare increment from free diffusion is not sensitive to the value change of diffusive technology share δ^D.

To check the potential impact of slightly different definition of diffusion share, I examine an alternative calibration method.[46] I use the data of import of royalties and license fees only, to calculate the value of goods produced by diffusive technology based on royalties and license fees. According to the statistical analysis of royalty rates from the Licensing Executives Society, many industries use about 5% of the selling price as a typical royalty rate, but rates can vary from 0.1 to

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[44] I use uniform trade costs and diffusion barriers in the sensitivity tests to save computation time.

[45] Meanwhile, it is not surprising to note that assuming all technology as diffusive technology suppresses the gains from free trade compared to the benchmark.

[46] Also see footnote 29.

25% or more and depend on the industry. I use average 5% royalty rate to calculate the value of goods produced by diffusive technology (V_i^D) for all countries except for Ireland. I use the average royalty rate 20% (software industry) for Ireland. By this way, I construct a rough measure of total value of goods produced by diffusive technology using imports of royalties and license fees. Its share of GDP is on average 8% in the sample, which doubles the previous data on royalties and license fees plus information intensive services. This is a royalty-calculated method. Because not all royalties and license fees are through royalty rate, some of them are fixed fees. It is possible to overestimate the real value of goods produced by diffusive technology. To be safe, in the benchmark, I use the first method based on payments associated with trade in royalties and license fees plus information intensive services. Those payments are on average 4% of GDP in the sample. I report the results from the royalty-calculated method in Table 15 which presents the results of welfare changes using the larger diffusion share data by royalty-calculated method to recalibrate the model and to redo the counterfactual exercises. It turns out that the main results are still robust: the welfare gains from free technology diffusion are still larger than the gains from free trade. Both the average and maximum welfare gains do not change much and are consistent with the intuition, i.e., increasing diffusion share slightly increases the gains from free diffusion and decreases the gains from free trade. The overall gains from free both diffusion and trade are increased.

6 Conclusion

This paper constructs and calibrates a general equilibrium model to assess the impact of technology diffusion and merchandise trade on welfare gains and cross-country distribution of GDP. The model features some countries as intermediaries that export goods produced by foreign technology through diffusion. In the model, the merchandise trade share and technology diffusion share are jointly determined in equilibrium. Using the data on payments associated with international technology diffusion, I calibrate the model to match the world GDP distribution, the technology diffusion shares, the merchandise trade shares, and real GDP per capita for a sample of 31 countries. The calibrated model replicates the technology diffusion and merchandise trade patterns, as well as GDP size and real GDP per capita across countries, fairly well.

I find that the welfare gains from removing diffusion barriers are generally larger than those from removing merchandise trade costs. This implies that the world has so far exploited more of the potential gains from reductions in the barriers to merchandize trade than the potential gains from reductions in the barriers to technology diffusion. Potential gains from further reduction of barriers to technology diffusion in the future are therefore higher than those from further reduction in trade costs. Removing diffusion barriers also increases merchandise trade, because countries are more likely to achieve higher productivity from obtaining foreign technology through diffusion and therefore improve their ability to export to the global market. In summary, free technology diffusion has greater welfare impact and contributes more to reducing the dispersion of real GDP per capita than does free merchandise trade. This calls for more attention to be paid to policies that help to reduce diffusion barriers.

The main contribution of this paper is the quantitative assessment of the welfare impact of technology diffusion and trade, as well as their impact on cross-country distribution of GDP, using market transaction data on technology diffusion and introducing diffusion barriers. It contributes to the literature exploring the gains from trade and to the literature simultaneously examining trade and technology diffusion. There are also some limitations. One concern is that the model assumes exogenous knowledge stock and that countries use existing knowledge for technology diffusion. If this assumption were relaxed, Eaton and Kortum (2006) predict that the gains from merchandise trade would not be affected by endogenous research efforts. However, the gains from technology diffusion have not been studied in the presence of endogenous knowledge creation. It is expected that endogenous knowledge creation would provide an incentive to knowledge producers and would potentially impact the pattern of technology specialization and diffusion process across countries. A thorough analysis of this issue seems fruitful and is left for future research. Another limitation is that the current findings are based on the assumption that country-specific diffusion barriers and trade costs exist between each country and the rest of the world as its partner. A more satisfactory model should capture bilateral diffusion barriers and trade costs between country pairs. If bilateral diffusion data are available, I can use the model to analyze the interaction between bilateral technology diffusion and bilateral merchandise trade. Finally, addressing the issue of extensive versus intensive margins in the technology market is also a direction worthy of exploring in future research. For this endeavor, it would be useful to acquire and construct firm-level data on payments associated with technology diffusion.

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A Derivation of Closed Economy Equilibrium

Let the unit price of individual tradables be $p(x)$. Denote the unit price of aggregate composite tradable goods by p_m. Finally, let the unit price of nontradable goods be $p_f(\tilde{x})$. Producers of all kinds will choose purchases of the individual tradable goods so as to obtain the composite intermediate at minimum unit cost p_m. Their question is

$$p_m Q = \min_{q(x)} \lambda \int_0^\infty e^{-\lambda x} p(x) q(x) dx$$

subject to

$$\left(\lambda \int_0^\infty e^{-\lambda x} q(x)^{1-1/\sigma} dx \right)^{\sigma/(\sigma-1)} \geq Q.$$

This problem is solved by the function

$$q(x) = \left(\lambda \int_0^\infty e^{-\lambda x} p(u)^{1-\sigma} du \right)^{\sigma/(1-\sigma)} p(x)^{-\sigma} Q. \tag{A.1}$$

Solving $q(x)$, it follows that the price index of composite intermediate is

$$p_m = \left(\lambda \int_0^\infty e^{-\lambda x} p(x)^{1-\sigma} dx \right)^{1/(1-\sigma)}. \tag{A.2}$$

The quantity of the individual tradable goods can be restated as

$$q(x) = p_m^\sigma p(x)^{-\sigma} Q. \tag{A.3}$$

Similarly, given the price w of the labor input and the aggregate tradable goods price p_m, tradable goods producer will choose the quantity of labor and aggregate inputs so as to minimize the expenditures on inputs. Hence, he will solve

$$p(x)q(x) = \min_{s, Q_m} [ws + p_m Q_m]$$

subject to

$$x^{-\theta} s^\beta Q_m^{1-\beta} \geq q(x).$$

This problem is solved by

$$s(x) = x^\theta \left(\frac{\beta}{1-\beta} \right)^{1-\beta} \left(\frac{p_m}{w} \right)^{1-\beta} q(x) \tag{A.4}$$

$$Q_m(x) = x^\theta \left(\frac{1-\beta}{\beta} \right)^\beta \left(\frac{w}{p_m} \right)^\beta q(x) \tag{A.5}$$

It follows that

$$p(x) = x^\theta B w^\beta p_m^{1-\beta} \tag{A.6}$$

where $B = \beta^{-\beta}(1-\beta)^{\beta-1}$. The unit cost of input bundle for tradable good is $c^T = Bw^\beta p_m^{1-\beta}$ and the unit price of tradable good is $x^\theta c^T$.

Finally, given the price w of the labor input and the composite intermediate price p_m, a final goods producer will solve

$$p_f(\tilde{x})q_f(\tilde{x}) = \min_{s_f, Q_f} [ws_f + p_m Q_f]$$

subject to

$$\tilde{x}^{-\theta} s_f^\alpha Q_f^{1-\alpha} \geq q_f(\tilde{x}).$$

This problem is solved by the values

$$s_f(\tilde{x}) = \left(\frac{\alpha}{1-\alpha}\right)^{1-\alpha} \left(\frac{p_m}{w}\right)^{1-\alpha} q_f(\tilde{x}) \tag{A.7}$$

$$Q_f(\tilde{x}) = \left(\frac{1-\alpha}{\alpha}\right)^{\alpha} \left(\frac{w}{p_m}\right)^{\alpha} q_f(\tilde{x}) \tag{A.8}$$

It follows that the unit price p of the final good is

$$p_f(\tilde{x}) = \tilde{x}^\theta A w^\alpha p_m^{1-\alpha} \tag{A.9}$$

where $A = \alpha^{-\alpha}(1-\alpha)^{\alpha-1}$ and the unit cost of the input bundle for final good is $c^{NT} = Aw^\alpha p_m^{1-\alpha}$. The unit price of final good is $\tilde{x}^\theta c^{NT}$.

Combining (A.2) and (A.6) and using the change of variable $z = \lambda x$, we have

$$\begin{aligned} p_m &= \left[\lambda \int_0^\infty e^{-\lambda x} \left(Bx^\theta w^\beta p_m^{1-\beta}\right)^{1-\sigma} dx\right]^{1/(1-\sigma)} \\ &= Bw^\beta p_m^{1-\beta} \lambda^{-\theta} \left[\int_0^\infty e^{-z} z^{\theta(1-\sigma)} dz\right]^{1/(1-\sigma)} \end{aligned} \tag{A.10}$$

We write $C(\theta, \sigma)$, or sometimes just C, for

$$C(\theta, \sigma) = \left[\int_0^\infty e^{-z} z^{\theta(1-\sigma)} dz\right]^{1/(1-\sigma)}. \tag{A.11}$$

C is a constant since the integral in brackets is the Gamma function $\Gamma(\xi)$, evaluated at the argument $\xi = 1 + \theta(1-\sigma)$. Convergence of the integral requires $1 + \theta(1-\sigma) > 0$, which we assume to hold throughout the paper.[47] Then we rewrite (A.10) as

$$p_m = CBw^\beta p_m^{1-\beta} \lambda^{-\theta}$$

Solving for p_m yields

$$p_m = (CB)^{1/\beta} \lambda^{-\theta/\beta} w. \tag{A.12}$$

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[47] Rodríguez-Clare (2007) explains why this assumption holds.

Substituting from (A.12) back into (A.6) then yields the prices of individual tradeables:

$$p(x) = C^{(1-\beta)/\beta} B^{1/\beta} x^{\theta} \lambda^{-\theta(1-\beta)/\beta} w. \tag{A.13}$$

The price of the final good is, from (A.9) and (A.12),

$$p_f = A(CB)^{(1-\alpha)/\beta} \tilde{x}^{\theta} \lambda^{-\theta(1-\alpha)/\beta} w. \tag{A.14}$$

To calculate the equilibrium quantities, we use the share formula as follows. The shares of labor and intermediate inputs in the output value of each tradable good x are β and $1-\beta$ respectively. Then the same equality must obtain for the composite aggregate:

$$\beta = \frac{w(1-s_f)}{p_m Q} \quad \text{and} \quad 1-\beta = \frac{Q_m}{Q} \tag{A.15}$$

Using (3.7) we have $Q_f = \beta Q$ and then the relative price formula (A.12) gives

$$1 - s_f = (CB)^{1/\beta} \lambda^{-\theta/\beta} Q_f. \tag{A.16}$$

Another equation of s_f and Q_f can be obtained from (A.7) and (A.8):

$$\frac{s_f}{Q_f} = \left(\frac{\alpha}{1-\alpha}\right)\left(\frac{p_m}{w}\right).$$

Using (A.12) again, we obtain

$$\frac{s_f}{Q_f} = \left(\frac{\alpha}{1-\alpha}\right)(CB)^{1/\beta} \lambda^{-\theta/\beta} \tag{A.17}$$

Combining two equations (A.16) and (A.17), we can solve for s_f and Q_f:

$$s_f = \alpha \quad \text{and} \quad Q_f = (1-\alpha)(CB)^{-1/\beta} \lambda^{\theta/\beta}. \tag{A.18}$$

From these equations, all equilibrium quantities can be calculated, just as equilibrium prices can be calculated from (A.12)-(A.14).

B Derivation of Open Economy Equilibrium

Let $g(x^E, x^D)$ and $G(x^E, x^D)$ be the joint density and the joint distribution respectively, of x^E and x^D, where x^E and x^D are two vectors: $x^E = (x_1^E, x_2^E, ..., x_I^E)$, $x^D = (x_1^D, x_2^D, ..., x_I^D)$. Use $q_n(x^E, x^D)$ for the consumption of tradable good (x^E, x^D) in country n, and Q_n for consumption of the aggregates in country n,

$$\begin{aligned} Q_n &= \left[\int q_n(x^E, x^D)^{1-1/\sigma} g(x^E, x^D) d(x^E, x^D)\right]^{\sigma/(\sigma-1)} \\ &= \left[\int q_n(x^E, x^D)^{1-1/\sigma} dG(x^E, x^D)\right]^{\sigma/(\sigma-1)} \end{aligned} \tag{B.1}$$

Let $p_n(x^E, x^D)$ be the prices paid for tradable good (x^E, x^D) by producers in country n. Let

$$p_{mn} = \left[\int p_n(x^E, x^D) dG(x^E, x^D)\right]^{1/(1-\sigma)} \tag{B.2}$$

be the price in country n for a unit of the aggregate. Analogous to previous section, we have

$$q_n(x^E, x^D) = p_{mn}^{\sigma} p_n(x^E, x^D)^{-\sigma} Q_n, \quad n = 1, ..., I. \tag{B.3}$$

All producers in n buy at the same, lowest price:

$$\begin{aligned} p_n(x^E, x^D) &= \min\{\min_i (x_i^E)^\theta c_i^T / k_{ni}, \min_{i,m} (x_i^D)^\theta c_{mi}^T / k_{nm}\} \\ &= \min\left\{\min_i (x_i^E)^\theta \frac{c_i^T}{k_{ni}}, \min_{i,m} (x_i^D)^\theta \frac{c_m^T}{b_{mi} k_{nm}}\right\} \end{aligned} \tag{B.4}$$

where $c_i^T = B w_i^\beta p_{mi}^{1-\beta}$, $i = 1, ..., I$.

Then we derive an expression for p_{mn} from (B.2) and (B.4). The derivation is based on two properties of the exponential distribution.[48] Then from (B.2), we obtain

$$p_{mn}^{1-\sigma} = \int p_n(x^E, x^D)^{1-\sigma} dG(x^E, x^D), \tag{B.5}$$

From (B.4), we have

$$p_n(x^E, x^D)^{1/\theta} = B^{1/\theta} \min\left\{\min_i \left[\frac{w_i^{\beta/\theta} p_{mi}^{(1-\beta)/\theta}}{k_{ni}^{1/\theta}} x_i^E\right], \min_{i,m} \left[\frac{w_m^{\beta/\theta} p_{mm}^{(1-\beta)/\theta}}{(b_{mi} k_{nm})^{1/\theta}} x_i^D\right]\right\} \tag{B.6}$$

By properties of exponential distribution, we have that $z_i^E \equiv w_i^{\beta/\theta} p_{mi}^{(1-\beta)/\theta} k_{ni}^{-1/\theta} x_i^E$ is exponentially distributed with parameter

$$\psi_{ni}^E = \left(\frac{w_i^\beta p_{mi}^{1-\beta}}{k_{ni}}\right)^{-1/\theta} \lambda_i^E \tag{B.7}$$

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[48] These properties are: (1) if $x \sim exp(\lambda)$ and $k > 0$ then $kx \sim exp(\lambda/k)$; and (2) if x and y are independent, $x \sim exp(\lambda)$ and $y \sim exp(\mu)$, then $\min\{x, y\} \sim exp(\lambda + \mu)$.

and $z_i^D \equiv \min_m \left\{ w_m^{\beta/\theta} p_{mm}^{(1-\beta)/\theta} (b_{mi}k_{nm})^{-1/\theta} x_i^D \right\}$ is exponentially distributed with parameter

$$\psi_{ni}^D = \min_m \left(\frac{w_m^\beta p_{mm}^{1-\beta}}{b_{mi}k_{nm}} \right)^{-1/\theta} \lambda_i^D \tag{B.8}$$

Then $z_i \equiv \min_i\{z_i^E, z_i^D\}$ is exponentially distributed with parameter $\psi_{ni} \equiv \psi_{ni}^E + \psi_{ni}^D$.[49] Applying the property of exponential distribution again yields that $p_n(x^E, x^D)^{1/\theta}$ is exponentially distributed with parameter

$$\mu = B^{-1/\theta}\psi_n \quad \text{where} \quad \psi_n \equiv \sum_{i=1}^{I} \psi_{ni}$$

Let $u = p_n(x^E, x^D)^{1/\theta}$. It then follows from (B.5) that

$$p_{mn}^{1-\sigma} = \mu \int_0^\infty u^{\theta(1-\sigma)} e^{-\mu u} du.$$

Using the change of variable $z = \mu u$, we obtain that

$$p_{mn}^{1-\sigma} = \mu^{-\theta(1-\sigma)} \int_0^\infty e^{-z} z^{\theta(1-\sigma)} dz = \mu^{-\theta(1-\sigma)} C^{1-\sigma}$$

where $C = C(\theta, \sigma)$ is the constant defined in section 3.1. Then

$$\begin{aligned} p_{mn}(w) &= CB \left(\sum_{i=1}^{I} \psi_{ni} \right)^{-\theta} \\ &\equiv (CB) \left(\sum_{i=1}^{I} \left(\left(\frac{w_i^\beta p_{mi}(w)^{1-\beta}}{k_{ni}} \right)^{-1/\theta} \lambda_i^E + \min_m \left(\frac{w_m^\beta p_{mm}(w)^{1-\beta}}{b_{mi}k_{nm}} \right)^{-1/\theta} \lambda_i^D \right) \right)^{-\theta} \end{aligned} \tag{B.9}$$

where $i, m = 1, ..., I$.

We then calculate the total value of goods associated with inward technology diffusion M_{ni}^D from country i to country n. Compared to the simple model with only tradable sector, now M_{ni}^D is comprised of two parts: technology diffusion used in tradable goods, $M_{ni}^{D,T}$, plus the corresponding value for technology diffusion used in consumption goods, $M_{ni}^{D,NT}$. Since these goods are non-tradable, it is necessary to derive an expression for the share of consumption goods v bought by country n that are produced with diffused technology from country i. Hence, I need the explicit price formula for final goods, p_f. Similar to tradable goods price (B.4), in country n

$$p_{fn}(\tilde{x}^E, \tilde{x}^D) = \min\{(\tilde{x}_n^E)^\theta c_n^{NT}, \min_i (\tilde{x}_i^D)^\theta c_{ni}^{NT}\} \tag{B.10}$$

where $\tilde{x}^E \sim exp(\lambda^E)$, $\tilde{x}^D \sim exp(\lambda^D)$, and $c_{ni}^{NT} = c_n^{NT}/b_{ni}$. Similar to equation (B.9), by properties

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[49] Compared to Section 2 with only tradable sector, there is a positive constant correlation between ψ and ϕ, where $\phi^{-\theta} = B\psi^{-\theta}$.

of exponential distribution, I derive the price index of nontradable goods in country n

$$p_{fn} = C\varphi_n^{-\theta} \tag{B.11}$$

where φ_n plays the similar role for consumption goods as ϕ_n for intermediate goods, with

$$\varphi_n \equiv \varphi_{nn}^E + \sum_i \varphi_{ni}^D \tag{B.12}$$

where $\varphi_{nn}^E = (c_n^{NT})^{-1/\theta}\lambda_n^E$ reflects the impact of exclusive technology on nontraded goods, and $\varphi_{ni}^D = (c_{ni}^{NT})^{-1/\theta}\lambda_i^D$ reflects the impact of diffusive technology on nontraded goods. Once the prices are determined, the equilibrium quantities can be derived as in the closed economy analysis. The allocations in the equilibrium have been illustrated in Section 3.2.

C Data and More Tables

Table 7: Country Data (ordered by GDP size)

Country	Size GDP as % of world GDP	Merchandise trade (imports/GDP) (V_i)	technology diffusion (inward diffusion/GDP) (V_i^D)	Real GDP per capita (US=1)	Relative population (US=1)
United States	27.18	0.10	0.01	1.00	1.00
Japan	15.24	0.07	0.02	0.83	0.46
Germany	7.59	0.20	0.04	0.79	0.30
France	5.05	0.20	0.02	0.72	0.22
United Kingdom	4.31	0.23	0.04	0.69	0.21
Italy	4.20	0.17	0.03	0.73	0.21
China	2.63	0.17	0.02	0.09	4.35
Brazil	2.24	0.07	0.01	0.24	0.59
Canada	2.21	0.28	0.04	0.76	0.11
Spain	2.08	0.19	0.02	0.60	0.14
Mexico	1.40	0.25	0.02	0.27	0.34
Russia	1.39	0.15	0.03	0.27	0.54
Netherland	1.33	0.45	0.07	0.80	0.06
Australia	1.29	0.16	0.03	0.72	0.07
India	1.29	0.10	0.01	0.07	3.48
Switzerland	0.95	0.28	0.03	0.95	0.03
Belgium and Luxembourg	0.94	0.59	0.08	0.79	0.04
Argentina	0.90	0.08	0.02	0.35	0.13
Sweden	0.89	0.24	0.05	0.73	0.03
Turkey	0.87	0.15	0.02	0.17	0.23
Austria	0.73	0.30	0.09	0.83	0.03
Denmark	0.58	0.25	0.04	0.76	0.02
Norway	0.51	0.22	0.05	0.89	0.02
Greece	0.50	0.19	0.02	0.52	0.04
South Africa	0.48	0.19	0.02	0.23	0.15
Finland	0.44	0.23	0.05	0.66	0.02
Portugal	0.38	0.31	0.03	0.48	0.04
Israel	0.32	0.30	0.05	0.60	0.02
Ireland	0.25	0.47	0.16	0.66	0.01
New Zealand	0.19	0.23	0.05	0.55	0.01
Hungary	0.15	0.43	0.07	0.33	0.04

Table 8: Country's technology state, GDP, trade costs, and diffusion barriers

country	λ_i (calibrated)	GDP (data)	GDP (model)	merchandise trade costs (calibrated)	technology diffusion barriers (calibrated)
United States	1.0000	1.0000	1.0000	0.6599	0.5878
Japan	0.5008	0.5609	0.5609	0.3541	0.5459
Germany	0.3379	0.2793	0.2793	0.6969	0.5928
France	0.2341	0.1856	0.1856	0.6481	0.5146
United Kingdom	0.2045	0.1585	0.1585	0.6739	0.5370
Italy	0.1975	0.1544	0.1544	0.6020	0.5181
China	0.1299	0.0966	0.0966	0.5528	0.4363
Brazil	0.1053	0.0823	0.0823	0.4025	0.4022
Canada	0.1130	0.0815	0.0815	0.6690	0.4905
Spain	0.1062	0.0764	0.0764	0.5662	0.4562
Mexico	0.0755	0.0517	0.0517	0.5851	0.4092
Russia	0.0734	0.0512	0.0512	0.4754	0.4534
Netherland	0.0642	0.0488	0.0488	0.8777	0.5010
Australia	0.0692	0.0476	0.0476	0.4897	0.4321
India	0.0660	0.0473	0.0473	0.4012	0.3880
Switzerland	0.0493	0.0350	0.0350	0.3505	0.4272
Belgium and Luxembourg	0.0490	0.0345	0.0345	0.7702	0.4764
Argentina	0.0477	0.0332	0.0332	0.3684	0.3838
Sweden	0.0502	0.0326	0.0326	0.5333	0.4503
Turkey	0.0482	0.0320	0.0320	0.4401	0.3773
Austria	0.0422	0.0270	0.0270	0.5808	0.4882
Denmark	0.0344	0.0213	0.0213	0.5075	0.4188
Norway	0.0307	0.0188	0.0188	0.4706	0.4226
Greece	0.0301	0.0184	0.0184	0.4454	0.3640
South Africa	0.0292	0.0178	0.0178	0.4435	0.3577
Finland	0.0268	0.0161	0.0161	0.4696	0.4064
Portugal	0.0233	0.0139	0.0139	0.5321	0.3749
Israel	0.0200	0.0116	0.0116	0.5066	0.3940
Ireland	0.0144	0.0092	0.0092	0.6945	0.4565
New Zealand	0.0129	0.0070	0.0070	0.4172	0.3670
Hungary	0.0097	0.0056	0.0056	0.5874	0.3711

Table 9: Change of Log Welfare Gains (%) by Country

$(log(con_1/con_0)) * 100$

country	free technology diffusion ($b = 1$)	free merchandise trade ($k = 1$)	free both ($b = 1, k = 1$)
United States	4.8092	8.5717	13.3915
Japan	9.5632	14.8861	24.4734
Germany	12.7404	14.4825	27.2102
France	16.7876	17.1885	33.9654
United Kingdom	18.0953	17.3614	35.4376
Italy	18.5823	18.9124	37.4897
China	23.7994	22.1311	45.9274
Brazil	26.4951	25.6547	52.1672
Canada	25.2351	20.0558	45.2580
Spain	26.1960	22.9513	49.1375
Mexico	30.8006	24.1553	54.9340
Russia	30.8843	26.8981	57.7847
Netherland	32.1362	13.6487	45.6947
Australia	31.8010	26.9533	58.7529
India	32.6218	28.7790	61.4144
Switzerland	38.9692	31.3746	67.6831
Belgium and Luxembourg	35.9247	18.5349	54.3821
Argentina	37.0011	31.3528	68.3833
Sweden	35.8793	27.5480	63.4089
Turkey	36.9104	30.0825	66.9957
Austria	37.5664	26.7223	64.2530
Denmark	41.2518	30.1195	71.3511
Norway	42.7284	31.8196	74.5354
Greece	43.5285	32.6503	76.1713
South Africa	43.9858	32.9903	76.8435
Finland	44.7932	32.5380	77.3159
Portugal	47.0380	30.8380	77.8386
Israel	48.9556	32.4719	81.3939
Ireland	51.9132	23.7249	75.5522
New Zealand	55.4087	37.9240	93.3167
Hungary	59.3049	30.2992	113.5795

Table 10: Change of Log Welfare Gains (%) If Only Productivity Shock in Tradable Sector

(consumption equivalence)

$(log(con_1/con_0)) * 100$

From benchmark to:	Average 31 countries	Maximum among 31 countries
free trade and diffusion ($k = 1, b = 1$)	26.0884	54.4346
only free trade ($k = 1$)	25.2975	38.3504
only free diffusion ($b = 1$)	0.0369	0.9589

Table 11: Real GDP Per Capita and its Change (%) by Country

country	benchmark	free diffusion (log change)	free trade (log change)	free both (log change)
United States	1.0000	1.0000 (-)	1.0000 (-)	1.0000 (-)
Japan	0.9268	0.9719 (4.75)	0.9872 (6.31)	1.0354 (11.08)
Germany	0.9166	0.9923 (7.93)	0.9725 (5.91)	1.0525 (13.82)
France	0.7947	0.8958 (11.98)	0.8662 (8.62)	0.9762 (20.57)
United Kingdom	0.6978	0.7970 (13.29)	0.7619 (8.79)	0.8699 (22.05)
Italy	0.6704	0.7694 (13.77)	0.7435 (10.34)	0.8531 (24.10)
China	0.0192	0.0233 (18.99)	0.0220 (13.56)	0.0266 (32.54)
Brazil	0.1073	0.1333 (21.69)	0.1273 (17.08)	0.1581 (38.78)
Canada	0.6830	0.8378 (20.43)	0.7661 (11.48)	0.9393 (31.87)
Spain	0.4579	0.5671 (21.39)	0.5287 (14.38)	0.6547 (35.75)
Mexico	0.1308	0.1697 (25.99)	0.1529 (15.58)	0.1982 (41.54)
Russia	0.0764	0.0991 (26.08)	0.0917 (18.33)	0.1190 (44.39)
Netherland	0.7248	0.9526 (27.33)	0.7625 (5.08)	1.0012 (32.30)
Australia	0.5872	0.7691 (26.99)	0.7057 (18.38)	0.9242 (45.36)
India	0.0103	0.0136 (27.81)	0.0126 (20.21)	0.0167 (48.02)
Switzerland	0.9652	1.3583 (34.16)	1.2125 (22.80)	1.6612 (54.29)
Belgium and Luxembourg	0.7439	1.0154 (31.12)	0.8218 (9.96)	1.1208 (40.99)
Argentina	0.1899	0.2620 (32.19)	0.2384 (22.78)	0.3290 (54.99)
Sweden	0.8326	1.1360 (31.07)	1.0066 (18.98)	1.3729 (50.02)
Turkey	0.1079	0.1488 (32.10)	0.1338 (21.51)	0.1844 (53.60)
Austria	0.7618	1.0570 (32.76)	0.9134 (18.15)	1.2668 (50.86)
Denmark	0.8812	1.2686 (36.44)	1.0931 (21.55)	1.5732 (57.96)
Norway	0.9138	1.3351 (37.92)	1.1529 (23.25)	1.6842 (61.14)
Greece	0.3614	0.5322 (38.72)	0.4597 (24.08)	0.6770 (62.78)
South Africa	0.0896	0.1325 (39.18)	0.1143 (24.42)	0.1689 (63.45)
Finland	0.6624	0.9880 (39.98)	0.8417 (23.97)	1.2552 (63.92)
Portugal	0.2904	0.4430 (42.23)	0.3628 (22.27)	0.5532 (64.45)
Israel	0.4534	0.7050 (44.15)	0.5758 (23.90)	0.8949 (68.00)
Ireland	0.5068	0.8118 (47.10)	0.5898 (15.15)	0.9437 (62.16)
New Zealand	0.3775	0.6261 (50.60)	0.5062 (29.35)	0.8394 (79.93)
Hungary	0.1047	0.1806 (54.50)	0.1301 (21.73)	0.2852 (100.19)

Notes: $(log(gdpp_{new}/gdpp_{bench})) * 100$ in parentheses.

Table 12: Merchandise Trade Share (V_i) by Country Under Different Scenarios

country	benchmark	free diffusion	free trade	free both
United States	0.0870	0.0881	0.3683	0.3688
Japan	0.0199	0.0203	0.4340	0.4343
Germany	0.1930	0.1948	0.4555	0.4557
France	0.1949	0.1966	0.4692	0.4693
United Kingdom	0.2273	0.2291	0.4731	0.4732
Italy	0.1762	0.1777	0.4740	0.4741
China	0.1727	0.1742	0.4829	0.4830
Brazil	0.0757	0.0765	0.4861	0.4862
Canada	0.2842	0.2861	0.4851	0.4852
Spain	0.2016	0.2032	0.4860	0.4861
Mexico	0.2510	0.2527	0.4901	0.4901
Russia	0.1511	0.1524	0.4903	0.4904
Netherland	0.4478	0.4486	0.4915	0.4916
Australia	0.1686	0.1700	0.4909	0.4909
India	0.0966	0.0975	0.4913	0.4913
Switzerland	0.0739	0.2024	0.4935	0.4935
Belgium and Luxembourg	0.4237	0.4247	0.4936	0.4936
Argentina	0.0889	0.0889	0.4937	0.4937
Sweden	0.2397	0.2414	0.4934	0.4934
Turkey	0.1492	0.1505	0.4936	0.4937
Austria	0.3039	0.3056	0.4944	0.4945
Denmark	0.2485	0.2502	0.4955	0.4955
Norway	0.2182	0.2199	0.4960	0.4960
Greece	0.1921	0.1936	0.4960	0.4961
South Africa	0.1926	0.1941	0.4961	0.4962
Finland	0.2298	0.2314	0.4965	0.4965
Portugal	0.3124	0.3141	0.4969	0.4969
Israel	0.2998	0.3015	0.4974	0.4974
Ireland	0.4552	0.4559	0.4981	0.4981
New Zealand	0.2335	0.2352	0.4983	0.4983
Hungary	0.4273	0.4283	0.4987	0.4967

Table 13: Sensitivity tests for the share of diffusive technology

δ^D	0.7	0.9	0.99	0.9999999999
k	0.5518	0.5517	0.5419	0.5560
b	0.3196	0.3078	0.2882	0.1264

Table 14: Robustness Check for Change of Welfare Gains (%) if all technologies are diffusive ($\delta^D = 1$)

(consumption equivalence)

$(log(con_1/con_0)) * 100$

	Average 31 countries	Maximum among 31 countries
free trade and free diffusion ($k = 1, b = 1$)	61.17	160.56
only free trade in goods ($k = 1$)	20.41	27.42
only free technology diffusion ($b = 1$)	34.84	82.12

Table 15: Robustness Check for Change of Welfare Gains (%) Using Larger Diffusion Share Data by Royalty-calculated Method

(consumption equivalence)

$(log(con_1/con_0)) * 100$

	Average 31 countries	Maximum among 31 countries
free trade and free diffusion $(k = 1, b = 1)$	60.93	116.39
only free trade in goods $(k = 1)$	24.94	37.91
only free technology diffusion $(b = 1)$	35.33	60.87