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Abstract

Almost 80 percent of capital goods production in the world is concentrated in 10 countries. Poor countries import most of their capital goods. We argue that international trade in capital goods has quantitatively important effects on economic development through two channels: (i) capital formation and (ii) aggregate TFP. We embed a multi country, multi sector Ricardian model of trade into a neoclassical growth model. Barriers to trade result in a misallocation of factors both within and across countries. We calibrate the model to bilateral trade flows, prices, and income per worker. Our model matches several trade and development facts within a unified framework. It is consistent with the world distribution of capital goods production, cross-country differences in investment rate and price of final goods, and cross-country equalization of price of capital goods and marginal product of capital. The cross-country income differences decline by more than 50 percent when distortions to trade are eliminated, with 80 percent of the change in each country's income attributable to change in capital. Autarky in capital goods results in an income loss of 17 percent for poor countries, with all of the loss stemming from decreased capital.

Keywords: Income differences; Capital goods trade; Investment rate; TFP.
JEL Classification: O11, O4, F11, E22.

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1 Introduction

Cross-country differences in income per worker are large: The income per worker in the top decile is more than 40 times the income per worker in the bottom decile (Penn World Tables version 6.3; see Heston, Summers, and Aten, 2009). Development accounting exercises such as those by Caselli (2005), Hall and Jones (1999), and Klenow and Rodríguez-Clare (1997) show that approximately 50 percent of the differences in income per worker are accounted for by differences in factors of production (capital and labor) and the rest is attributed to differences in aggregate total factor productivity (TFP).

One strand of the literature on economic development explains the income differences via misallocation of factors in *closed economies*. For instance, in Buera, Kaboski, and Shin (2011) and Greenwood, Sanchez, and Wang (2013), financial frictions prevent capital from being employed efficiently.[1] We argue that closed economy models can provide only part of the reason for cross-country differences in capital. Two facts motivate our argument: (i) capital goods production is concentrated in a few countries and (ii) the dependence on capital goods imports is negatively related to income level. Ten countries account for almost 80 percent of world capital goods production. Capital goods production is more concentrated than gross domestic product (GDP); 16 countries account for 80 percent of the world's GDP. The second fact is that the imports-to-production ratio for capital goods is negatively correlated with economic development: The correlation between the ratio and income per worker is -0.26. Malawi imports 47 times as much capital goods as it produces, Argentina imports twice as much as it produces, while the US imports only half as much as it produces.

In this paper, international trade in capital goods has quantitatively important effects on cross-country income differences through two channels: capital formation and aggregate TFP. International trade enables poor countries to access capital goods produced in rich countries. Barriers to capital goods trade result in less capital accumulation in poor countries since, relative to the world frontier, the rate of transformation of consumption into investment is lower. Barriers to trade also result in countries producing goods for which they do not have a comparative advantage. Poor countries, for instance, do not have a comparative advantage in producing capital goods, but they allocate too many resources to producing capital goods relative to non-capital goods. Thus, trade barriers result in an inefficient allocation of factors across sectors within a country and affect the country's aggregate TFP. A reduction in barriers would induce each country to specialize more in the direction of its comparative advantage, resulting in a reduction in cross-country factor and TFP differences.

We develop a multi country Ricardian trade model along the lines of Dornbusch, Fischer,

[1] Restuccia and Rogerson (2008) study misallocation of labor in a closed economy.

and Samuelson (1977), Eaton and Kortum (2002), Alvarez and Lucas (2007), and Waugh (2010). Each country is endowed with labor that is not mobile internationally. Each country has technologies for producing a final consumption good, structures, a continuum of capital goods, a continuum of intermediate goods (i.e., non-capital goods), and a composite intermediate good. All of the capital goods and intermediate goods can be traded. Neither the final consumption good nor structures can be traded. Countries differ in their distributions of productivities in both capital goods and intermediate goods. Trade barriers are assumed to be bilateral iceberg costs. We model other domestic distortions via final goods productivity in each country. In contrast to the above trade models, cross-country differences in factors of production are endogenous in our model.

Differences in income per worker in our model are a function of (i) differences in development accounting elements, such as final goods productivity and capital per worker, and (ii) differences in additional elements, such as barriers to trading capital goods and intermediate goods, and average productivities in capital goods and intermediate goods sectors. Trade barriers and sectoral productivities affect how much of the investment in a country is due to domestic capital goods production and how much is due to trade, which in turn affects the amount of capital per worker in the country. Furthermore, in our model, measured TFP is directly affected by trade barriers and sectoral productivities, similar to Waugh (2010).

We calibrate the model to be consistent with the observed bilateral trade in capital goods and intermediate goods, the observed relative prices of capital goods and intermediate goods, and income per worker. Our model fits these targets well. For instance, the correlation in home trade shares between the model and the data is 0.97 for both capital goods and intermediate goods; the correlation between model and data income per worker is 0.99.

Our model reconciles several trade and development facts in a unified framework. First, we account for the fact that a few countries produce most of the capital goods in the world: In our model and in the data, 10 countries account for 79 percent of the world capital goods production. The pattern of comparative advantage in our model is such that poor countries are net importers of capital goods and net exporters of intermediate goods. The average productivity gap in the capital goods sector between countries in the top and bottom income deciles is almost three times as large as the gap in the intermediate goods sector.

Second, the capital per worker in our model is consistent with the data; the correlation between the model and the data is 0.93. Capital per worker in the top decile is 52 times that in the bottom decile in our model; the corresponding number in the data is 48. The log variance of capital per worker in our model is 92 percent of that in the data. The contribution of factor differences in accounting for income differences in our model is similar to the contribution in the data. That is, development accounting in the model and in the data yields similar results.

Third, we deliver the facts that the investment rate measured in domestic prices is uncorrelated with income per worker and the investment rate measured in international prices is positively correlated with income per worker, facts noted previously by Restuccia and Urrutia (2001) and Hsieh and Klenow (2007). In domestic prices, the investment rate in the model is constant across countries. In international prices, the correlation in the model between the investment rate and income per worker is 0.7, and in the data the correlation is 0.54. In contrast to Restuccia and Urrutia (2001), we do not treat the price of investment relative to final goods as exogenous; instead, each country's relative price of investment is determined in equilibrium along with domestic savings rates and cross-country capital goods flows. Furthermore, our model is consistent with the fact that the relative price of investment is negatively correlated with income per worker. In contrast to Hsieh and Klenow (2007), investment in our model is consistent with the observed production and international flows of capital goods. Their model has only two tradable goods and complete specialization, so by design a country that imports capital goods will not produce any. Consequently, their model cannot deliver the observed trade and production pattern in capital goods.

Fourth, our model is consistent with observed prices. As Hsieh and Klenow (2007) point out, the price of capital goods is roughly the same across countries and the relative price of capital is higher in poor countries because the price of the nontradable consumption good is lower in poor countries. Both in our model and in the data, the elasticity of the price of capital goods with respect to income per worker is 0.03. The elasticity of the price of consumption goods is 0.57 in the model and 0.52 in the data. Our model is also consistent with the fact that the price of structures is positively correlated with economic development.

Fifth, our model delivers cross-country equalization of the marginal product of capital. In response to the question of why capital does not flow from rich to poor countries posed by Lucas (1990), Caselli and Feyrer (2007) argued that the real marginal product of capital is roughly equal across countries if it is measured using the observed relative price of capital. We deliver this fact in a trade theoretic framework where both the flow of capital and the relative price of capital are endogenous and consistent with the data. Stated differently, the equalization of the marginal product of capital in our model does not come at the cost of counterfactual implications for trade flows and prices.

To quantify the effect of trade barriers, we compare our benchmark specification with a world that has no trade barriers. The world without barriers allocates capital (and other factors) optimally, both across countries and across sectors within a country. Relative to this world, countries with a comparative disadvantage in capital goods in our benchmark model allocate too many resources to the production of capital goods, which leads to both reduced capital formation and lower aggregate TFP in poor countries. In the world without trade barriers, the gap in capital per worker between countries in the top and bottom deciles of the income distribution is 7; the corresponding gap is 52 in the benchmark. Consequently, the cross-country income differences are smaller with zero trade barriers: The gap in income per worker is only 10.2, while in the benchmark it is 22.5. In each country roughly 80 percent of the increase in income from the benchmark to the world without trade barriers is accounted for by the increase in capital. That is, eliminating trade barriers increases income predominantly through increases in capital, a channel that is absent in Alvarez and Lucas (2007) and Waugh (2010).

In the absence of capital goods trade (i.e., autarky in the capital goods sector but trade subject to barriers in the intermediate goods sector), poor countries have to rely on domestic production for capital goods. This implies that the world operates further inside its production possibilities frontier and every country suffers an income loss. Countries in the bottom decile suffer an income loss of 17 percent, on average, with some countries experiencing as much as a 30 percent loss in income. For all of the countries, the income loss is almost entirely accounted for by the decreases in the capital stock.

In both counterfactuals the relative price of capital plays a key role. As trade barriers change, the relative price of capital changes. That is, the amount of consumption good that a household has to give up in order acquire a unit of investment changes. This, in turn, affects the amount of capital goods imports and the investment rate. Consequently, the capital per worker changes and so does income. (See Hsieh, 2001, for evidence on the effect of trade barriers on the relative price of capital, capital goods imports, and investment rates.)

The rest of the paper is organized as follows. Section 2 develops the multi country Ricardian trade model and describes the steady state equilibrium. Section 3 describes the calibration. The quantitative results are presented in Section 4. Section 5 concludes.

2 Model

Our model extends the framework of Eaton and Kortum (2002), Alvarez and Lucas (2007), and Waugh (2010) to two tradable sectors and embeds it into a neoclassical growth framework (see also Mutreja, 2013). There are I countries indexed by $i = 1, \dots, I$. Time is discrete and runs from $t = 0, 1, \dots, \infty$. There are two tradable sectors, capital goods and intermediates (or non-capital goods), and two nontradable sectors, structures and final goods. (We use "producer durables" and "capital goods" interchangeably.) The capital goods and intermediate goods sectors are denoted by e and m, respectively. Investment in structures, denoted by s, augments the existing stock of structures. The final good, denoted by f, is used only for consumption. Within each tradable sector, there is a continuum of goods. Individual capital goods in the continuum are aggregated into a composite producer durable, which augments the stock of producer durables. Individual intermediate goods are aggregated into a composite intermediate good. The composite intermediate good is an input in all sectors.

Each country i has a representative household with a measure L_i of workers.[2] Labor is immobile across countries but perfectly mobile across sectors within a country. The household owns its country's stock of producer durables and stock of structures. The respective capital stocks are denoted by K_{it}^e and K_{it}^s. They are rented to domestic firms. Earnings from capital and labor are spent on consumption and investments in producer durables and structures. The two investments augment the respective capital stocks. Henceforth, all quantities are reported in per worker units (e.g., $k^e = K^e/L$ is the stock of producer durables per worker) and, where it is understood, country and time subscripts are omitted.

2.1 Technology

Each country has access to technologies for producing all capital goods, all intermediate goods, structures, and the final good. All technologies exhibit constant returns to scale.

Tradable sectors Each capital good in the continuum is indexed by v, while each intermediate good is indexed by u. Production of each tradable good requires capital, labor, and the composite intermediate good. As in Eaton and Kortum (2002), the indices u and v represent idiosyncratic draws for each good in the continuum. These draws come from country- and sector-specific distributions, with densities denoted by φ_{bi} for $b \in \{e, m\}$, and $i = 1, \ldots, I$. We denote the joint density across countries for each sector by φ_b.

Composite goods All individual capital goods in the continuum are aggregated into a composite producer durable E according to

$$E = \left[\int q_e(v)^{\frac{\eta-1}{\eta}} \varphi_e(v) dv \right]^{\frac{\eta}{\eta-1}},$$

where $q_e(v)$ denotes the quantity of good v. Similarly, all individual intermediate goods in the continuum are aggregated into a composite intermediate good M according to

$$M = \left[\int q_m(u)^{\frac{\eta-1}{\eta}} \varphi_m(u) du \right]^{\frac{\eta}{\eta-1}}.$$

[2] We have also solved the model using efficiency units of labor constructed via years of schooling and Mincer returns. We also allowed for growth over time in the number of workers, as well as growth in the efficiency units of labor. None of these extensions affect our quantitative results.

Individual goods in the continuum All individual goods are produced using the capital stock, labor, and the composite intermediate good.

The technologies for producing individual goods in each sector are given by

$$e(v) = v^{-\theta} \left[\left(k_e^e(v)^{\mu} k_e^s(v)^{1-\mu} \right)^{\alpha} \ell_e(v)^{1-\alpha} \right]^{\nu_e} M_e(v)^{1-\nu_e}$$
$$m(u) = u^{-\theta} \left[\left(k_m^e(u)^{\mu} k_m^s(u)^{1-\mu} \right)^{\alpha} \ell_m(u)^{1-\alpha} \right]^{\nu_m} M_m(u)^{1-\nu_m}.$$

For each factor used in production, the subscript denotes the sector that uses the factor, the argument in the parentheses denotes the index of the good in the continuum, and the superscript on the two capital stocks denotes either producer durables or structures. For example, $k_e^s(v)$ is the stock of structures used to produce capital good v. The parameter $\nu \in (0, 1)$ determines the share of value added in production, while $\alpha \in (0, 1)$ determines capital's share in value added. The parameter μ controls the share of producer durables relative to structures.

The variables u and v are distributed exponentially. In country i, v has an exponential distribution with parameter $\lambda_{ei} > 0$, while u has an exponential distribution with parameter $\lambda_{mi} > 0$. Then, factor productivities, $v^{-\theta}$ and $u^{-\theta}$, have Fréchet distributions, implying average factor productivities of λ_e^{θ} and λ_m^{θ}. If $\lambda_{ei} > \lambda_{ej}$, then on average, country i is more efficient than country j at producing capital goods. Average productivity at the sectoral level determines specialization across sectors. Countries for which λ_e/λ_m is high will tend to be net exporters of capital goods and net importers of intermediate goods. The parameter $\theta > 0$ governs the coefficient of variation of factor productivity. A larger θ implies more variation in productivity draws across individual goods within each sector and, hence, more room for specialization within each sector. We assume that the parameter θ is the same across the two sectors and in all countries.[3]

Nontradable goods Recall that final goods and structures are nontradable. The final good is consumed by the household. It is produced using capital, labor, and intermediate goods according to

$$F = A_f \left[\left((k_f^e)^{\mu} (k_f^s)^{1-\mu} \right)^{\alpha} \ell_f^{1-\alpha} \right]^{\nu_f} M_f^{1-\nu_f},$$

where A_f denotes (country-specific) TFP in final goods production.

Structures are produced similarly:

$$S = \left[\left((k_s^e)^{\mu} (k_s^s)^{1-\mu} \right)^{\alpha} \ell_s^{1-\alpha} \right]^{\nu_s} M_s^{1-\nu_s}.$$

[3] In Section 3.1 we provide separate estimates of θ for the two sectors. Our estimates are nearly identical.

Capital accumulation As in the standard neoclassical growth model, the representative household enters each period with predetermined stocks of producer durables and structures. The stocks of producer durables and structures are accumulated according to

$$k_{t+1}^e = (1-\delta_e)k_t^e + x_t^e \text{ and}$$
$$k_{t+1}^s = (1-\delta_s)k_t^s + x_t^s,$$

where δ_e and δ_s are the depreciation rates of producer durables and structures respectively. The terms x_t^e and x_t^s denote investments in the two types of capital stocks in period t. Country i's investment in structures is the same as country i's production of structures, S, since structures are not traded. Investment in producer durables is the composite of the continuum of producer durables, E, which consists of domestic production and imports.

We define the aggregate capital stock per worker as

$$k = (k^e)^\mu (k^s)^{1-\mu}.$$

Preferences The representative household in country i derives utility from consumption of the final good according to

$$\sum_{t=0}^{\infty} \beta^t \log(c_{it}),$$

where c_{it} is consumption of the final (non-tradable) good in country i at time t, and $\beta < 1$ is the period discount factor.

International trade Country i purchases each individual capital good and each individual intermediate good from the least-cost suppliers. The purchase price depends on the unit cost of the supplier, as well as trade barriers.

Barriers to trade are denoted by τ_{bij}, where $\tau_{bij} > 1$ is the amount of sector b good that country j must export in order for one unit to arrive in country i. We normalize the barriers to ship goods domestically: $\tau_{bii} = 1$ for $b \in \{e, m\}$ and for all i.

We focus on a steady-state competitive equilibrium. Informally, a steady-state equilibrium is a set of prices and allocations that satisfy the following conditions: (i) The representative household maximizes lifetime utility, taking prices as given; (ii) firms maximize profits, taking factor prices as given; (iii) domestic markets for factors and nontradable goods clear; (iv) total trade is balanced in each country; and (v) prices and quantities are constant over time. Note that condition (iv) allows for the possibility of trade imbalances at the sectoral level, but a trade surplus in one sector must be offset by an equal deficit in the other sector. In the remainder of this section, we describe each condition from country i's point of view.

Cross-country differences in endogenous variables in our model are a function of differences in the exogenous endowment of labor, L_i; productivity parameters in the capital goods sector and intermediate goods sector, λ_e and λ_m, respectively; TFP in the final goods sector, A_f; and the trade barriers, τ_e and τ_m. The remaining parameters, $\alpha, \nu_e, \nu_m, \nu_s, \nu_f, \delta_e, \delta_s, \theta, \mu, \beta$, and η, are constant across countries.

2.2 Household optimization

At the beginning of each time period, the stocks of producer durables and structures are predetermined and are rented to domestic firms in all sectors at the competitive rental rates r_{eit} and r_{sit}. Each period the household splits its income between consumption, c_{it}, which has price P_{fit}, and investments in producer durables and in structures, x_{it}^e and x_{it}^s, which have prices P_{eit} and P_{sit}, respectively.

The household is faced with a standard consumption-savings problem, the solution to which is characterized by two Euler equations, the budget constraint, and two capital accumulation equations. In steady state these conditions are as follows:

$$r_{ei} = \left[\frac{1}{\beta} - (1-\delta_e)\right] P_{ei},$$
$$r_{si} = \left[\frac{1}{\beta} - (1-\delta_s)\right] P_{si},$$
$$P_{fi}c_i + P_{ei}x_i^e + P_{si}x_i^s = w_i + r_{ei}k_i^e + r_{si}k_i^s,$$
$$x_i^e = \delta_e k_i^e, \text{ and}$$
$$x_i^s = \delta_s k_i^s.$$

2.3 Firm optimization

Denote the price of intermediate good u that was produced in country j and imported by country i by $p_{mij}(u)$. Then, $p_{mij}(u) = p_{mjj}(u)\tau_{mij}$, where $p_{mjj}(u)$ is the marginal cost of producing good u in country j. Since each country purchases each individual good from the least cost supplier, the actual price in country i for the intermediate good u is $p_{mi}(u) = \min_{j=1,\dots,I} [p_{mjj}(u)\tau_{mij}]$. Similarly, the price of capital good v in country i is $p_{ei}(v) = \min_{j=1,\dots,I} [p_{ejj}(v)\tau_{eij}]$.

The prices of the composite producer durable and the composite intermediate good are

$$P_{ei} = \left[\int p_{ei}(v)^{1-\eta}\varphi_e(v)dv\right]^{\frac{1}{1-\eta}} \text{ and } P_{mi} = \left[\int p_{mi}(u)^{1-\eta}\varphi_m(u)du\right]^{\frac{1}{1-\eta}}.$$

We explain the derivation of the price indices for each country in Appendix A. Given the assumption on the country-specific densities, φ_{ei} and φ_{mi}, our model implies

$$P_{ei} = \gamma B_e \left[\sum_l \left(d_{el} \tau_{eil} \right)^{-1/\theta} \lambda_{el} \right]^{-\theta} \text{ and } P_{mi} = \gamma B_m \left[\sum_l \left(d_{ml} \tau_{mil} \right)^{-1/\theta} \lambda_{ml} \right]^{-\theta},$$

where the unit costs for input bundles d_{bi}, for each sector $b \in \{e, m\}$, are given by $d_{bi} = \left(r_{ei}^{\alpha} w_i^{1-\alpha} \right)^{\nu_b} P_{mi}^{1-\nu_b}$. The terms B_b for $b \in \{e, m, f, s\}$ are constant across countries and are given by $B_b = (\alpha \nu_b)^{-\alpha \nu_b} ((1-\alpha)\nu_b)^{(\alpha-1)\nu_b} (1-\nu_b)^{\nu_b - 1}$. Finally, $\gamma = \Gamma(1 + \theta(1-\eta))^{\frac{1}{1-\eta}}$, where $\Gamma(\cdot)$ is the gamma function. We restrict parameters such that $\gamma > 0$.

The prices of the final good and structures are simply their marginal costs:

$$P_{fi} = \frac{B_f d_{fi}}{A_{fi}} \text{ and } P_{si} = B_s d_{si}.$$

For each tradable sector the fraction of country i's expenditure on imports from country j is given by

$$\pi_{eij} = \frac{\left(d_{ej} \tau_{eij} \right)^{-1/\theta} \lambda_{ej}}{\sum_l \left(d_{el} \tau_{eil} \right)^{-1/\theta} \lambda_{el}} \text{ and } \pi_{mij} = \frac{\left(d_{mj} \tau_{mij} \right)^{-1/\theta} \lambda_{mj}}{\sum_l \left(d_{ml} \tau_{mil} \right)^{-1/\theta} \lambda_{ml}}.$$

An alternative interpretation of π_{bij} is that it is the fraction of sector b goods that j supplies to i. We describe the derivation of the trade shares in Appendix A.

2.4 Equilibrium

We first define total factor usage in the intermediate goods sector in country i as follows:

$$\begin{aligned}
\ell_{mi} &= \int \ell_{mi}(u) \varphi_{mi}(u) du, \\
k_{mi}^e &= \int k_{mi}^e(u) \varphi_{mi}(u) du, \\
k_{mi}^s &= \int k_{mi}^s(u) \varphi_{mi}(u) du, \text{ and} \\
M_{mi} &= \int M_{mi}(u) \varphi_{mi}(u) du,
\end{aligned}$$

where $\ell_{mi}(u), k_{mi}^e(u), k_{mi}^s(u)$, and $M_{mi}(u)$, respectively, refer to the amount of labor, stock of producer durables, stock of structures, and composite intermediate good used in country i to produce the intermediate good u. Note that each of $l_{mi}(u), k_{mi}^e(u), k_{mi}^s(u)$, and $M_{mi}(u)$ will take the value zero if country i imports good u. Total factor usage for the capital goods sector $(\ell_{ei}, k_{ei}^e, k_{ei}^s, M_{ei})$ is defined analogously.

The factor market clearing conditions in country i are

$$
\begin{aligned}
\ell_{ei} + \ell_{si} + \ell_{mi} + \ell_{fi} &= 1, \\
k_{ei}^e + k_{si}^e + k_{mi}^e + k_{fi}^e &= k_i^e, \\
k_{ei}^s + k_{si}^s + k_{mi}^s + k_{fi}^s &= k_i^s, \text{ and} \\
M_{ei} + M_{si} + M_{mi} + M_{fi} &= M_i.
\end{aligned}
$$

The left-hand side of each of the previous equations is simply the factor usage by each sector, while the right-hand side is the factor availability.

The next three conditions require that the quantity of consumption and investment goods purchased by the household must equal the amounts available in country i:

$$
c_i = F_i, x_i^e = E_i, \text{ and } x_i^s = S_i.
$$

Aggregating over all producers of individual goods in each sector of country i and using the fact that each producer minimizes costs, the factor demands at the sectoral level are

$$
\begin{aligned}
L_i w_i \ell_{bi} &= (1-\alpha)\nu_b Y_{bi}, \\
L_i r_{ei} k_{bi}^e &= \mu\alpha\nu_b Y_{bi}, \\
L_i r_{si} k_{bi}^s &= (1-\mu)\alpha\nu_b Y_{bi}, \text{ and} \\
L_i P_{mi} M_{bi} &= (1-\nu_b) Y_{bi},
\end{aligned}
$$

where Y_{bi} is the value of output in sector b. Imposing the goods market clearing condition for each sector implies that

$$
\begin{aligned}
Y_{ei} &= \sum_{j=1}^{I} L_j P_{ej} E_j \pi_{eji}, \\
Y_{mi} &= \sum_{j=1}^{I} L_j P_{mj} M_j \pi_{mji}, \\
Y_{si} &= L_i P_{si} S_i, \text{ and} \\
Y_{fi} &= L_i P_{fi} F_i.
\end{aligned}
$$

The total expenditure by country j on capital goods is $L_j P_{ej} E_j$, and π_{eji} is the fraction spent by country j on capital goods imported from country i. Thus, the product, $L_j P_{ej} E_j \pi_{eji}$, is the total value of capital goods trade flows from country i to country j.

To close the model we impose balanced trade country by country:

$$
L_i P_{ei} E_i \sum_{j \neq i} \pi_{eij} + L_i P_{mi} M_i \sum_{j \neq i} \pi_{mij} = \sum_{j \neq i} L_j P_{ej} E_j \pi_{eji} + \sum_{j \neq i} L_j P_{mj} M_j \pi_{mji}.
$$

The left-hand side denotes country i's imports of capital goods and intermediate goods, while the right-hand side denotes country i's exports. This condition allows for trade imbalances at the sectoral level within each country; however, a surplus in capital goods must be offset by an equal deficit in intermediates and vice versa.

2.5 Discussion of the model

Our model provides a tractable framework for studying how trade affects capital formation, measured TFP, and income per worker. We define real income per worker to be $y = (w + rk)/P_f$. In our model, the income per worker in country i can be written as

$$y_i \propto A_{fi} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\theta \frac{1-\nu_f}{\nu_m}} k_i^{\alpha}. \tag{1}$$

In equation (1), λ_m and A_f are exogenous. The remaining components on the right-hand side of equation (1), namely, π_{mii} and k_i, are equilibrium objects.

Standard development accounting exercise would have the income per worker in the form $y = Z\,k^{\alpha}$ and measure TFP by Z. In our model, measured TFP is endogenous since the home trade share, π_{mii}, is an equilibrium object in equation (1). Cross-country differences in productivities and trade barriers affect the home trade shares in each country.

Cross-country differences in productivities and trade barriers also imply differences in aggregate steady state capital per worker in our model. (Recall that the aggregate capital is a Cobb-Douglas aggregate of the stock of producer durables and the stock of structures: $k = (k^e)^{\mu}(k^s)^{1-\mu}$.) Appendix A shows that the capital per worker is a function of home trade shares and productivity parameters in the capital goods and intermediate goods sectors:

$$k_i \propto \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\theta \frac{1-\mu\nu_e-(1-\mu)\nu_s}{\nu_m(1-\alpha)}} \left(\frac{\lambda_{ei}}{\pi_{eii}}\right)^{\theta \frac{\mu}{1-\alpha}}. \tag{2}$$

The final goods sector productivity, A_f, does not affect the trade shares and, hence, does not affect the capital per worker; A_f simply scales income per worker.

Alvarez and Lucas (2007) and Waugh (2010) treat capital as an exogenous factor of production, so changes in trade barriers have no effect on cross-country differences in capital and the effect on income per worker implied by equation (2) is absent. As an extreme case, if ν_f equals 1 then a change in trade barriers will have no effect on economic development in their models, whereas there will be an effect in ours through capital per worker.

Equations (1) and (2) help us quantify the effect of trade barriers. Holding capital per worker and the productivity parameters fixed, a reduction in trade barriers reduces π_{mii} which increases measured TFP and income per worker. According to equation (1), a 1 percent reduction in the intermediate goods home trade share increases y directly via TFP by $\theta\frac{1-\nu_f}{\nu_m}$ percent; in our benchmark calibration (Table 1 in Section 3), this elasticity is 0.08. A reduction in trade barriers also increases capital per worker via (i) a reduction in π_{mii} and (ii) a reduction in π_{eii} (see equation (2)). The effect of trade barriers on economic development through capital per worker is as large as the effect through measured TFP in our model. For instance, 1 percent reduction in capital goods home trade share increases y by $\theta\frac{\mu\alpha}{1-\alpha}$ percent; this elasticity is 0.07 in our benchmark calibration.

The basic one-sector growth model allows for endogenous capital formation as we do, but in that model the capital-output ratio is independent of TFP; in our model it is not. To see this, the income per worker in the one-sector growth model can be written more conveniently as $y = Z^{\frac{1}{1-\alpha}} \left(\frac{k}{y}\right)^{\frac{\alpha}{1-\alpha}}$. In steady state, the gross marginal product capital, which is a function of just $\frac{k}{y}$, is pinned down by the discount factor, so changes in Z have no effect on $\frac{k}{y}$.

In our model the corresponding expression for income per worker is

$$y_i \propto \left(A_{fi} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\theta\frac{1-\nu_f}{\nu_m}} \right)^{\frac{1}{1-\alpha}} \left(\frac{k_i}{y_i}\right)^{\frac{\alpha}{1-\alpha}},$$

where the capital-output ratio is given by

$$\frac{k_i}{y_i} \propto \frac{1}{A_{fi}} \left(\frac{\lambda_{ei}}{\pi_{eii}}\right)^{\theta\mu} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\theta\frac{\nu_f-\mu\nu_e-(1-\mu)\nu_s}{\nu_m}} \tag{3}$$

(see Appendix A). In our model, a change in measured TFP affects the capital-output ratio.

To summarize, trade affects economic development via measured TFP and capital formation. Comparative advantage parameters and barriers to international trade affect the extent of specialization in each country, which affects measured TFP and the relative price of capital goods. The price, in turn, affects the investment rate and, hence, the capital stock. In our quantitative exercise we discipline the model using relative prices, bilateral trade flows, and levels of development to explore the importance of capital goods trade.

3 Calibration

We calibrate our model using data for a set of 88 countries for the year 2005. This set includes both developed and developing countries and accounts for about 80 percent of world GDP in version 6.3 of the Penn World Tables (see Heston, Summers, and Aten, 2009). Our calibration strategy uses cross-country data on income per worker, bilateral trade and output for capital goods and intermediate goods, and prices of capital goods, intermediate goods, and final goods. Next we describe how we map our model to the data; details on specific countries, data sources, and data construction are described in Appendix B.

We begin by grouping disaggregate data such that the groups correspond to the model sectors. Capital goods and structures in the model correspond to the categories "Machinery and equipment" and "Construction", respectively, in the World Bank's International Comparisons Program (ICP).

For production and trade data for capital goods we use two-digit International Standard Industrial Classification (ISIC) categories that coincide with the definition of "Machinery and equipment" used by the ICP; specifically, we use categories 29-35 in revision 3 of the ISIC. Production data are from INDSTAT2, a database maintained by UNIDO. The corresponding trade data are available at the four-digit level from Standard International Trade Classification (SITC) revision 2. We follow the correspondence created by Affendy, Sim Yee, and Satoru (2010) to link SITC with ISIC categories. Intermediate goods correspond to the manufacturing categories other than capital goods, i.e., categories 15-28 and 36-37 in revision 3 of the ISIC. We repeat the above procedure to assemble the production and trade data for intermediate goods.

Prices of capital goods and structures come directly from the 2005 benchmark study of the Penn World Tables (PWT). We construct the price of intermediate goods by aggregating across all nondurable goods categories (excluding services) in the 2005 benchmark study. The price of final goods corresponds to "Price level of consumption" in version 6.3 of PWT. Our measure of income per worker is also from version 6.3 of PWT.

3.1 Common parameters

We begin by describing the parameter values that are common to all countries (Table 1). The discount factor β is set to 0.96, in line with common values in the literature. Following Alvarez and Lucas (2007), we set $\eta = 2$ (this parameter is not quantitatively important for the questions addressed in this paper).

As noted earlier, the capital stock in our model is $k = (k^e)^{\mu}(k^s)^{1-\mu}$. The share of capital in GDP, α, is set at 1/3, as in Gollin (2002). Using capital stock data from the Bureau of Economic Analysis (BEA), Greenwood, Hercowitz, and Krusell (1997) measure the rates of depreciation for both producer durables and structures. We set our values in accordance with their estimates: $\delta_e = 0.12$ and $\delta_s = 0.06$. We also set the share of producer durables in composite capital, μ, at 0.56 in accordance with Greenwood, Hercowitz, and Krusell (1997).

The parameters ν_m, ν_e, ν_s, and ν_f, respectively, control the shares of value added in intermediate goods, capital goods, structures, and final goods production. To calibrate ν_m and ν_e,

Table 1: Parameters common across countries

Parameter	Description	Value
α	k's Share	0.33
ν_m	k and ℓ's Share in intermediate goods	0.31
ν_e	k and ℓ's Share in capital goods	0.31
ν_s	k and ℓ's Share in structures	0.39
ν_f	k and ℓ's Share in final goods	0.90
δ_e	Depreciation rate of producer durables	0.12
δ_s	Depreciation rate of structures	0.06
θ	Variation in (sectoral) factor productivity	0.25
μ	Share of producer durables in composite capital	0.56
β	Discount factor	0.96
η	Elasticity of substitution in aggregator	2

we use the data on value added and total output available in the INDSTAT2 2013 database. To determine ν_s, we compute value added shares in gross output for construction for a set of 32 countries in Organization for Economic Cooperation and Development (OECD), and average across these countries. Data on value added and gross output for OECD countries are from input-output tables in the STAN database maintained by OECD for the period "mid 2000s" (http://stats.oecd.org/Index.aspx). We set the value of ν_s at 0.39. To calibrate ν_f we use the same input-output tables. The share of intermediates in final goods is $1 - \nu_f$. Our estimate of ν_f is 0.9. (Alvarez and Lucas, 2007, compute a share of 0.82 by excluding agriculture and mining from the final goods sector. Since we include agriculture and mining in final goods we obtain a larger estimate.)

Estimating θ The parameter θ in our model controls the dispersion in factor productivity. We follow the procedure of Simonovska and Waugh (2014) to estimate θ (see Appendix C for a description of their methodology).

We estimate θ for (i) all manufactured goods (producer durables + intermediate goods), (ii) only intermediate goods, and (iii) only producer durables. Our estimate for all manufactured goods is 0.27 (Simonovska and Waugh, 2014, obtain an estimate of 0.25). Our estimate for the capital goods sector is 0.23; for the intermediate goods sector it is 0.25. In light of these similar estimates, we take $\theta = 0.25$ as our preferred value for both sectors.[4]

[4]Our estimate of θ and the parameters in Table 1 satisfy the restriction imposed by the model: $\beta < 1$ and $1 + \theta(1 - \eta) > 0$.

3.2 Country-specific parameters

Country-specific parameters in our model are labor force, L; productivity parameters in the capital goods and intermediate goods sectors, λ_e and λ_m, respectively; productivity in the final goods sector, A_f; and the bilateral trade barriers, τ_{eij} and τ_{mij}. We take the labor force in each country from Penn World Tables version 6.3 (PWT63, see Heston, Summers, and Aten, 2009). The other country-specific parameters are calibrated to match a set of targets.

Bilateral trade barriers Using data on prices and bilateral trade shares, in both capital goods and intermediate goods, we calibrate the bilateral trade barriers in each sector using a structural relationship implied by our model:

$$\frac{\pi_{bij}}{\pi_{bjj}} = \left(\frac{P_{bj}}{P_{bi}}\right)^{-1/\theta} \tau_{bij}^{-1/\theta}, b \in \{e, m\}. \tag{4}$$

We set $\tau_{bij} = 100$ for bilateral country pairs where $\pi_{bij} = 0$.

Countries in the bottom decile of the income distribution have substantially larger barriers to export capital goods than countries in the top decile. If we take all of the countries in the bottom decile and look at their barriers to export to all of the countries in our sample, 70 percent of those barriers are larger than 13 and only 1.5 percent are less than 4. Conversely, for the countries in the top decile, only 9 percent of the export barriers are larger than 13 and almost 70 percent are less than 4.

Another way to summarize this feature is by computing a trade-weighted export barrier for country i as $\frac{1}{X_{bi}} \sum_{j \neq i} \tau_{bij} X_{bji}$, where X_{bji} is country i's exports to country j in sector $b \in \{e, m\}$ and X_{bi} is country i's total exports in that sector. The trade weighted export barrier in the capital goods sector for countries in the bottom income decile is 4.51 while for countries in the top decile it is 1.94. The calibrated trade barriers in intermediate goods display a similar pattern: The trade weighted export barrier for poor countries is 6.49 while for rich countries it is 1.60.

Productivities Using data on relative prices, home trade shares, and income per worker, we use the model's structural relationships to calibrate $\lambda_{ei}, \lambda_{mi}$, and A_{fi}. The structural relationships are given by

$$\frac{P_{mi}/P_{fi}}{P_{mUS}/P_{fUS}} = \frac{A_{fi}}{A_{fUS}} \left(\frac{\lambda_{mi}/\pi_{mii}}{\lambda_{mUS}/\pi_{mUSUS}} \right)^{-\theta \frac{\nu_f}{\nu_m}}, \tag{5}$$

$$\frac{P_{ei}/P_{fi}}{P_{eUS}/P_{fUS}} = \frac{A_{fi}}{A_{fUS}} \left(\frac{\lambda_{ei}/\pi_{eii}}{\lambda_{eUS}/\pi_{eUSUS}} \right)^{-\theta} \left(\frac{\lambda_{mi}/\pi_{mii}}{\lambda_{mUS}/\pi_{mUSUS}} \right)^{\theta \frac{\nu_e - \nu_f}{\nu_m}}, \tag{6}$$

$$\frac{y_i}{y_{US}} = \frac{A_{fi}}{A_{fUS}} \left(\frac{\lambda_{ei}/\pi_{eii}}{\lambda_{eUS}/\pi_{eUSUS}} \right)^{\theta \frac{\mu\alpha}{1-\alpha}} \left(\frac{\lambda_{mi}/\pi_{mii}}{\lambda_{mUS}/\pi_{mUSUS}} \right)^{-\theta \frac{1-\nu_f + \frac{\alpha}{1-\alpha}(1+\mu\nu_e + (1-\mu)\nu_s)}{\nu_m}}. \tag{7}$$

We normalize $\lambda_{eUS}, \lambda_{mUS}$, and A_{fUS} equal to 1 and simultaneously solve for $\lambda_{ei}, \lambda_{mi}$, and A_{fi} for each country i (see Appendix A for derivations of the equations). None of the objects that we discuss in our results depend on this normalization. For instance, the value of λ_{eUS}/A_{fUS} does not affect our results so long as λ_{ei}/A_{fi} is scaled proportionally in every country i. Indeed, the prices that we use are all relative to the US so we can only identify the parameters up to the US value.

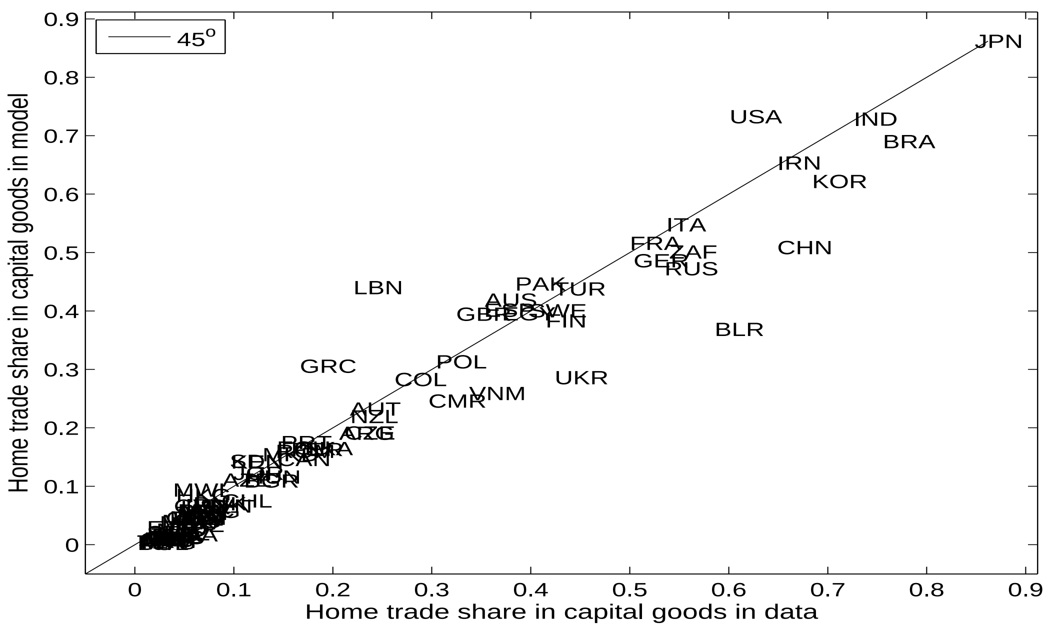
Table D.1 in Appendix D presents the calibrated productivity parameters. The average productivity gap in the capital goods sector between countries in the top and bottom deciles is 4.5. In the intermediate goods sector the average productivity gap is 1.6. That is, rich countries have a comparative advantage in capital goods production, while poor countries have a comparative advantage in intermediate goods production. Thus, the model is consistent with the observation that poor countries are net importers of capital goods.

3.3 Model fit

With I countries, our model is overidentified by $2(I-1)$ data points. We have calibrated $2I(I-1)$ trade barriers: τ_{eij} and τ_{mij} $(j \neq i)$ and $3(I-1)$ productivity parameters: $\lambda_{ei}, \lambda_{mi}$, and A_{fi}, $(i \neq US)$. That is, we determined the values of $(2I+3)(I-1)$ parameters. In order to identify these parameters we used $(2I+5)(I-1)$ data points: $2I(I-1)$ bilateral trade shares (π_{eij} and π_{mij} $(j \neq i)$), $I-1$ prices of capital goods (P_{ei} relative to the US), $I-1$ prices of intermediate goods (P_{mi} relative to the US), $I-1$ prices of capital goods relative to final goods (P_{ei}/P_{fi} relative to the US), $I-1$ prices of intermediate goods relative to final goods (P_{mi}/P_{fi} relative to the US), and $I-1$ observations on income per worker (y_i relative to the US). As a consequence of the overidentification, our model might not exactly match all of the data points.

Trade shares Figure 1 plots the home trade shares in capital goods, π_{eii}, in the model against the data. The observations line up close to the 45-degree line; the correlation between the model and the data is 0.97. The home trade shares for intermediate goods also line up closely with the data; the correlation is 0.97. The correlation between bilateral trade shares (excluding the home trade shares) in the model and that in the data is 0.94 in the capital goods sector and 0.91 in the intermediate goods sector.

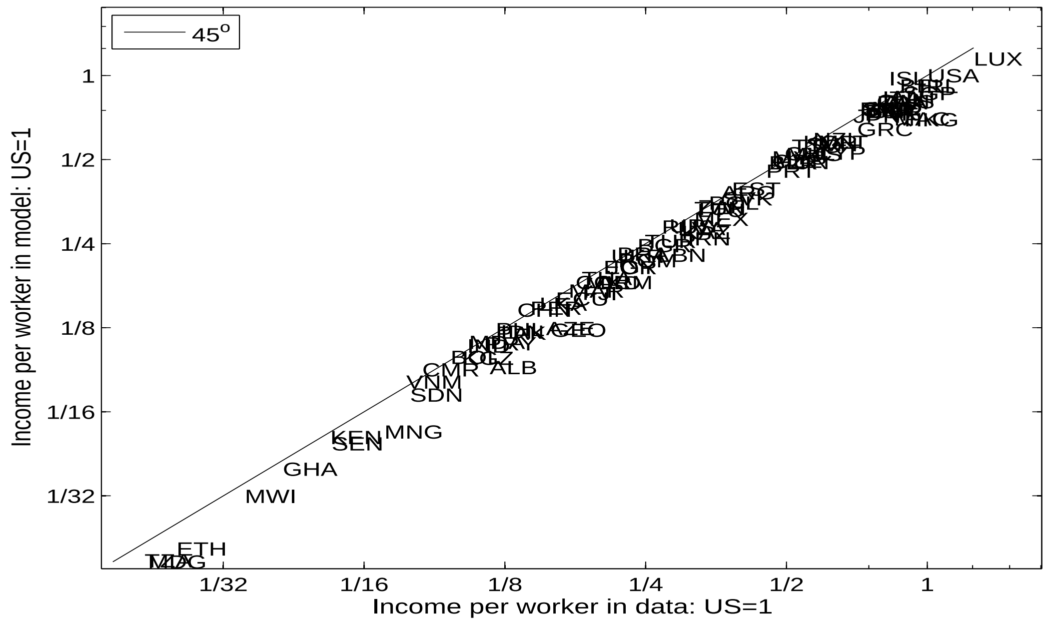
Figure 1: Home trade share in capital goods



Prices The correlations between the model and the data for the absolute price of capital goods, the relative price of capital goods, the absolute price of intermediate goods, and the relative price of intermediate goods are 0.95, 0.94, 0.98, and 0.93, respectively.

Income per worker Figure 2 illustrates the relative income per worker in the model and in the data. The correlation between the model and the data is 0.99. Log variance in the final goods sector productivity (A_f) accounts for 25 percent of the log variance in income per worker. (Recall from equations (1) and (2) that changes in A_f do not affect home trade shares and capital per worker.) This does *not* imply that factors account for the remaining 75 percent since measured TFP is not just A_f but includes exogenous components, such as λ_{mi}, and endogenous components, such as π_{mii}.

Figure 2: Income per worker, US=1



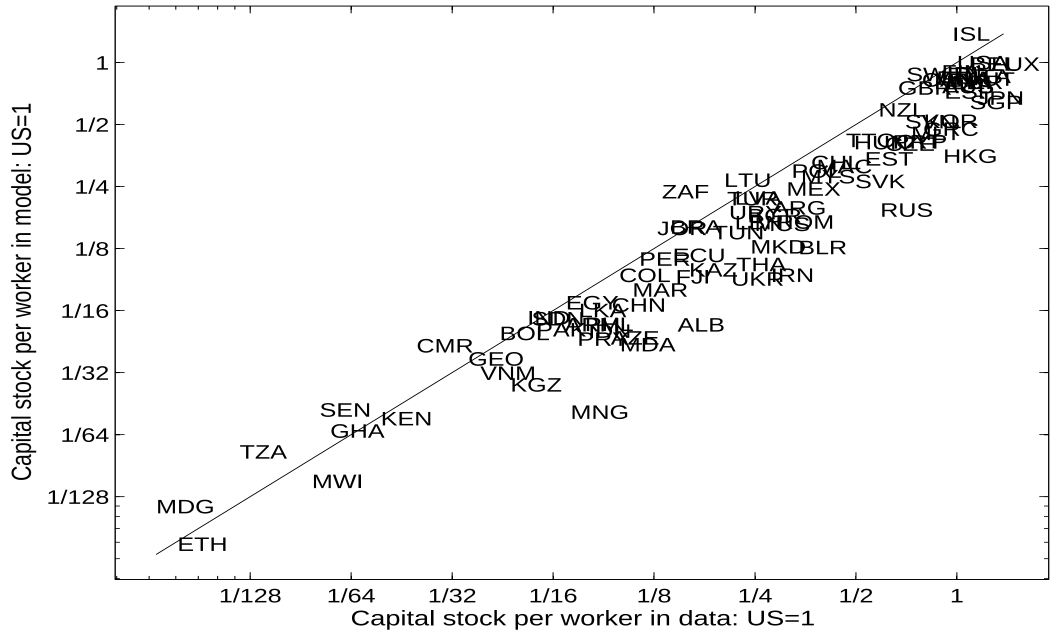
4 Results

Capital formation Equation (2) explicitly shows how trade in intermediate goods and in capital goods affects capital per worker in each country. Figure 3 plots capital per worker in the model against that in the data. The correlation between the model and data for capital per worker is 0.93.

The model accounts for 92 percent of the observed log variance in capital per worker. Figure 3 coupled with the log variance result implies the following. Suppose we conduct a development accounting exercise along the lines of Caselli (2005) using the model's output: What fraction of the log variance in income per worker is accounted for by the log variance in factors? Given the model's fit for the income per worker (see Figure 2), the fraction attributed by the model would be similar to that implied by the data. Log variance in y accounted for by k^{α} is 19 percent in the model and 22 percent in the data. Measured TFP, which includes final goods sector productivity A_f, accounts for 34 percent of log variance in income per worker in the model and 31 percent in the data. (Recall from Section 3.3 that log variance in A_f alone accounts for 25 percent of the log variance of y in the model.) These results are consistent with the evidence in King and Levine (1994) who argue that capital is not a primary determinant of economic development.

The model also delivers a positive correlation between measured TFP and capital-output ratio (see equation (3)). In the data, the correlation is 0.39, while in the model it is 0.57.

Figure 3: Capital per worker, US=1



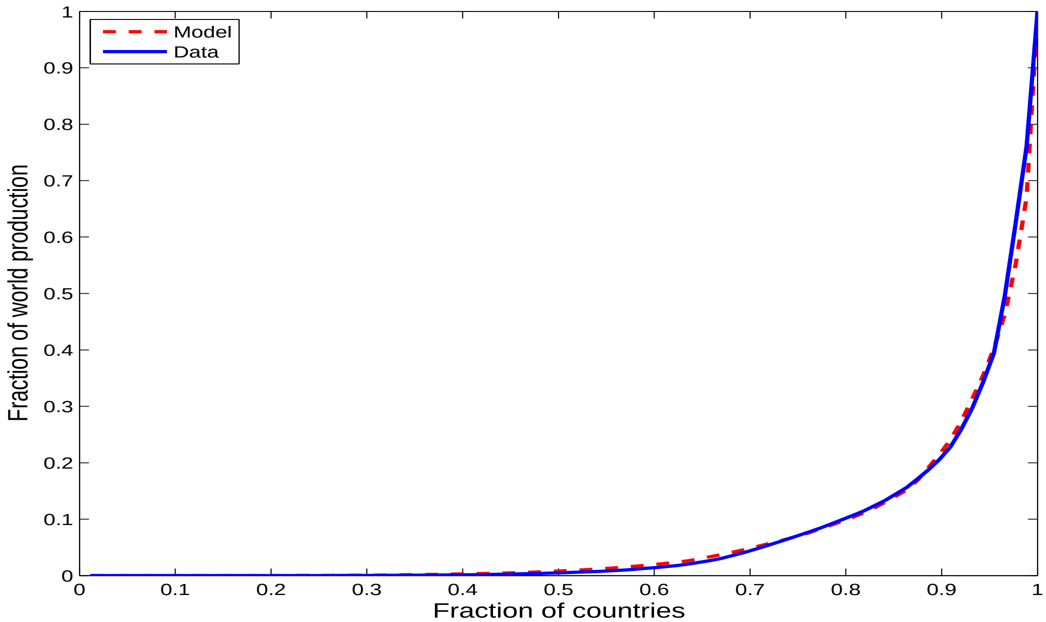
Capital goods production and trade flows Figure 4 illustrates the cdf for capital goods production. The model captures the observed skewness in production: In the model and in the data, 10 countries account for 79 percent of the world's capital goods production. The correlation between model and data for capital goods production is 0.94, so the countries do in fact line up correctly in Figure 4. Furthermore, poor countries are net importers of capital goods in the model and in the data and, as noted earlier, our model is consistent with the observed bilateral trade flows.

Prices In the data, while the *relative* price of capital is higher in poor countries, the absolute price of capital goods does not exhibit such a systematic variation with level of economic development. As noted in Section 3.3, our model is consistent with data on the absolute price of capital goods and the price relative to consumption goods. The elasticity of the absolute price (with respect to income per worker) is 0.03 in the model and in the data; the elasticity of the relative price is -0.54 in the model and -0.49 in the data.

Eaton and Kortum (2001) construct a "trade-based" price of capital goods using a gravity regression. Hsieh and Klenow (2007) point out that the constructed prices are not consistent with the data on capital goods prices. In particular, the constructed prices are higher in poor countries than in rich countries.

Hsieh and Klenow (2007) also point out that the negative correlation between the relative price of capital goods and economic development is mainly due to the price of consumption,

Figure 4: Distribution of capital goods production



which is lower in poor countries. Our model is consistent with this fact: price elasticity of consumption goods is 0.57 in our model and 0.52 in the data.

Finally, the price of structures (not one of the calibration targets) is positively correlated with income per worker; the price elasticity of structures is 0.60 in the model and 0.48 in the data.

Investment rates First, in our model, the investment rate measured in domestic prices is constant across countries, which is consistent with the data. Our model implies that in steady state $P_{ei}x_i^e = \phi_e r_{ei} k_i^e$ and $P_{si}x_i^s = \phi_s r_{si} k_i^s$, where $\phi_b = \frac{\delta_b}{(1)/\beta-(1-\delta_b)}$ for $b \in \{e, s\}$. Recall $k_i = (k_i^e)^\mu (k_i^s)^{1-\mu}$, so $r_{ei}k_i^e = \mu r_i k_i$ and $r_{si}k_i^s = (1-\mu) r_i k_i$. Since capital income $r_i k_i = w_i \alpha/(1-\alpha)$, $P_{ei}x_i^e = \phi_e \mu w_i \alpha/(1-\alpha)$ and $P_{si}x_i^s = \phi_s(1-\mu)w_i\alpha/(1-\alpha)$. Therefore, aggregate investment per worker is $P_{ei}x_i^e + P_{si}x_i^s = [\mu\phi_e + (1-\mu)\phi_s]w_i\alpha/(1-\alpha)$. Now, income is $w_i + r_i k_i = w_i/(1-\alpha)$, so the investment rate in domestic prices is

$$\frac{P_{ei}x_i^e + P_{si}x_i^s}{w_i + r_i k_i},$$

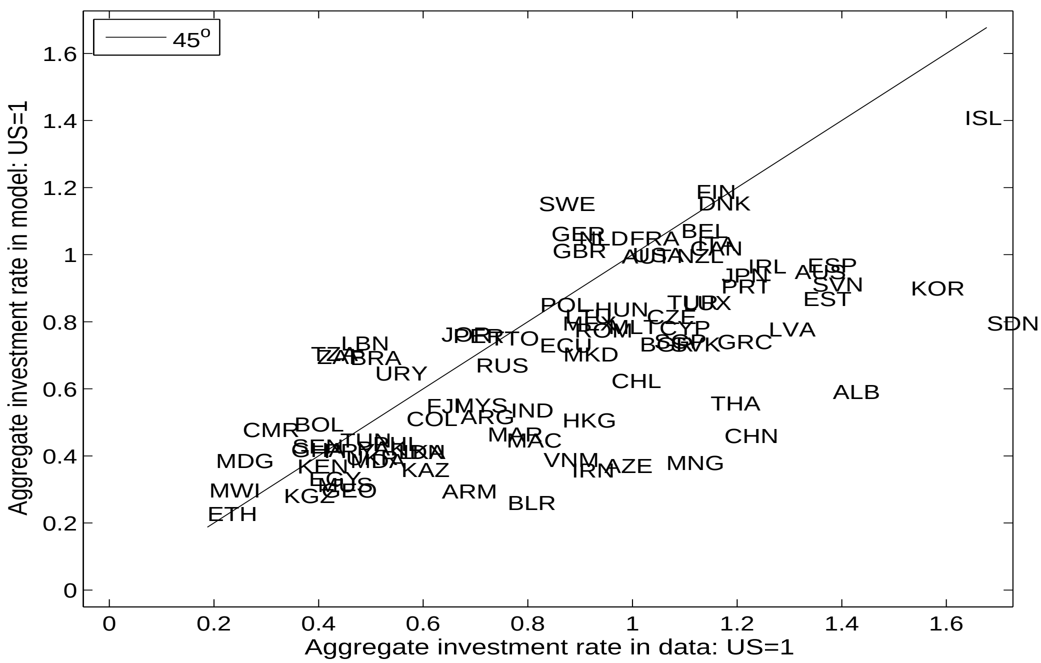
which is a constant $\alpha[\mu\phi_e + (1-\mu)\phi_s]$.

Second, our model captures the systematic variation in investment rates measured in international prices: Rich countries have higher investment rates than poor countries. The investment rate measured in purchasing power parity (PPP) prices for country i is given by

$$\frac{\frac{P_{ei}}{P_{xi}} x_i^e + \frac{P_{si}}{P_{xi}} x_i^s}{y_i},$$

where P_{xi} is the price index for aggregate investment in country i (see Appendix A). Figure 5 plots the investment rate across countries. The investment rate is positively correlated with economic development and the correlation between the model and the data is 0.68.

Figure 5: Investment rate in PPP: US=1



As discussed in Restuccia and Urrutia (2001), investment rates determine capital-output ratios and, hence, are crucial for understanding economic development. Taking the relative price of investment as exogenous, their model is able to account for 90 percent of the observed log variance in investment rates across countries. In our model, the relative price is endogenous; we account for 73 percent of the observed log variance.

Hsieh and Klenow (2007) infer that barriers to capital goods trade play no role in explaining investment rates across countries using the fact that capital goods prices do not exhibit strong systematic variation with income per worker. In our model, trade barriers play a key role in explaining relative price, investment rates, and the world distribution of capital goods production. In the capital goods sector, poor countries face a larger barrier to export and have lower productivity relative to rich countries. The negative correlation between trade barriers and productivity is essential to be consistent with both prices and trade flows; this is discussed in detail in Mutreja et al. (2012). Our calibrated productivities imply that poor countries have a comparative advantage in intermediate goods. However, with large barriers to trade, it is costly for poor countries to export intermediate goods in exchange for capital goods. This is reflected in the high relative price of capital in poor countries, leading to low investment rates and low capital per worker. In Hsieh and Klenow (2007), there are only two tradable goods, so the specialization is complete and the model is not designed to address the pattern of trade and production in capital goods. Our model produces the capital goods trade flows and prices that are in line with the data.

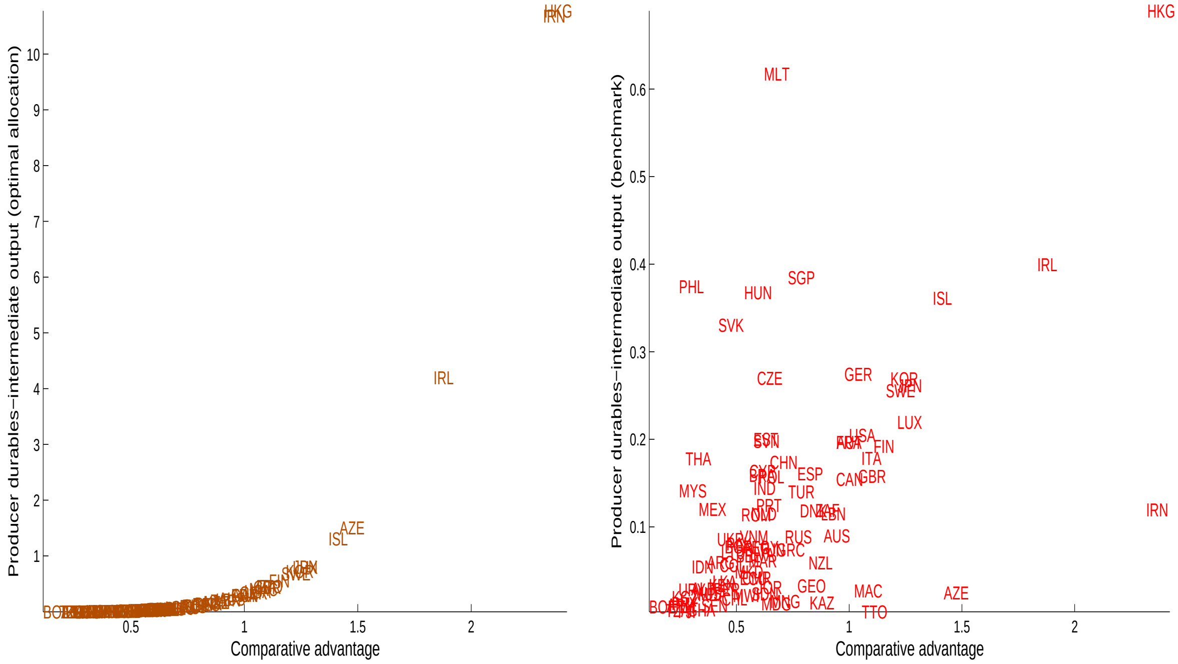
Marginal product of capital Since capital-labor ratios are larger in rich countries than in poor countries, a standard (closed economy) neoclassical growth model would imply that poor countries would have a higher marginal product of capital (MPK), so Lucas (1990) posed the question: Why doesn't capital flow from rich to poor countries? In response, Caselli and Feyrer (2007) use the fact that the relative price of capital is higher in poor countries to show that the real value of marginal product actually looks similar across countries. Thus, there is no MPK puzzle to begin with. In Appendix A, we show that our model implies that the real MPK is equal across countries. Moreover, the observed world pattern of capital goods production and flows as well as the relative prices of capital goods can be quantitatively reconciled with the marginal product of capital being equal across countries.

4.1 Misallocation due to trade barriers

In the benchmark model, trade barriers result in a misallocation of resources across sectors in each country. To determine the magnitude of the misallocation, we compare the allocation in the benchmark model with the optimal allocation in a world without trade distortions. In this exercise, we remove barriers to trade in both sectors by setting $\tau_{mij} = \tau_{eij} = 1$ for all countries and leaving all other parameters at their calibrated values. Clearly, the optimal allocation would dictate that countries with a comparative advantage in capital goods should produce more capital goods relative to intermediate goods. Figure 6 plots the optimal relative size of the capital goods sector (Y_{ei}/Y_{mi}) in each country in the left panel, and that for the benchmark model in the right panel.

In a world with distortions, the relative size of the capital goods sector is far from optimal. The production of capital goods, relative to intermediate goods, is too little in rich countries and too much in poor countries. In the benchmark economy, Thailand allocates 71 times as much labor to capital goods production relative to the optimal allocation, and France allocates only 0.73 times as much. The misallocation is drastically larger in poor countries than in rich countries.

Figure 6: Capital goods output relative to intermediate goods output: no distortion in trade (left), benchmark (right)



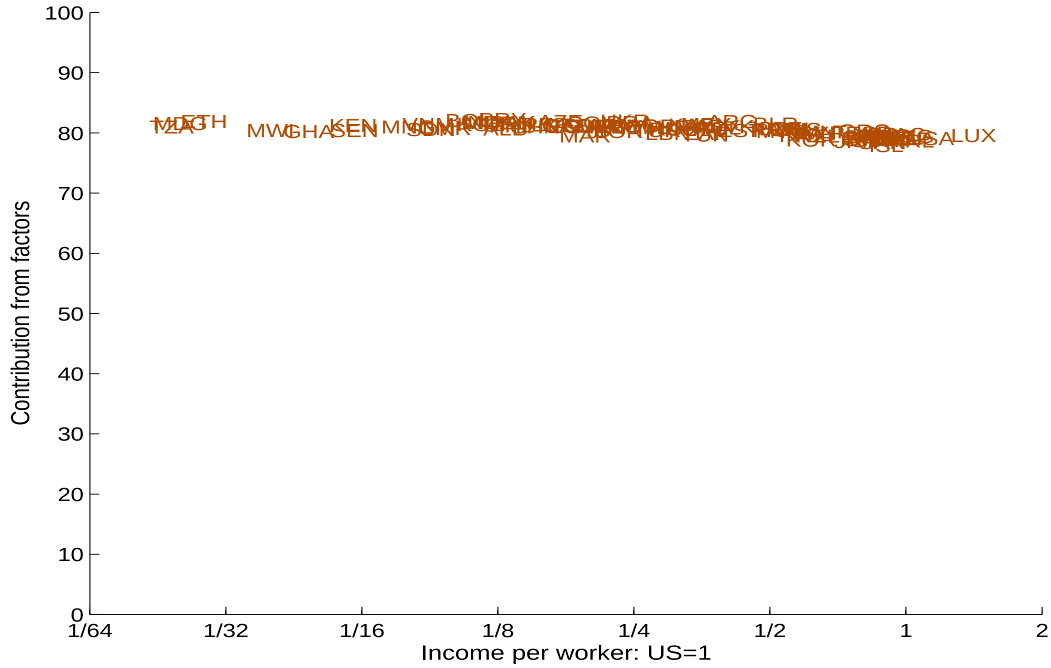
Note: Comparative advantage is measured as $(\lambda_e/\lambda_m)^\theta$

In a world without trade distortions, resources are allocated optimally. As a result, production of capital goods becomes more concentrated in the countries that have a comparative advantage in capital goods production. Thus, more capital goods are produced and traded, and countries accumulate more capital.

The gap between countries in the top and bottom deciles of the income distribution falls from 22.5 to 10.2. In each country, approximately 80 percent of the increase in income per worker can be attributed to increased capital and the remaining 20 percent to higher TFP (see Figure 7). The gap in capital per worker between countries in the top and bottom income deciles is a factor of only 7 in the optimal allocation, compared with a factor of 52 in the presence of trade barriers.

These results imply that capital being an endogenous factor of production is quantitatively important for examining the effect of trade barriers on development. In a world with exogenous factors of production such as Alvarez and Lucas (2007) and Waugh (2010), reductions in trade barriers increase income per worker only through higher TFP in equation (1), via lower home trade shares in intermediate goods. In our model reductions in trade barriers reduce home trade shares in both intermediate goods and in capital goods and increase the income per worker both because of higher TFP and because of higher capital per worker in

Figure 7: Fraction of change in income per worker due to change in capital per worker: benchmark to no distortion in trade



equation (2). Our results indicate that the second effect is nearly four times the first effect.

Trade barriers affect capital per worker in our model through the relative price of capital. In the presence of trade barriers, poor countries with a comparative disadvantage in capital goods production transform consumption into investment at an inferior rate relative to the world frontier. In the absence of barriers, poor countries can transform consumption into investment at a higher rate since they have access to a superior international production possibilities frontier. For instance, in our benchmark, Bolivia gets 24 units of capital goods for every unit of consumption, but with zero barriers Bolivia gets more than 500 units. Furthermore, Bolivia increases its aggregate investment rate more than 20-fold in response to the higher rate of transformation. The increase in investment rate, in turn, increases Bolivia's steady state capital per worker by a factor of 200.

The experience of Korea presents some evidence in favor of the channel in our model. Korea's trade reforms starting in 1960s reduced the restrictions on imports of capital goods (see Westphal, 1990; Yoo, 1993). During 1970-80, Korea's imports of capital goods increased 11-fold. Over a period of 40 years, the relative price of capital in Korea decreased by a factor of almost 2 and the investment rate increased by a factor of more than 4 (Nam, 1995). (See also Rodriguez and Rodrik, 2001, for a discussion of trade policies affecting relative prices.)

Hsieh (2001) provides evidence on the channel in our model via a contrast between Argentina and India. During the 1990s, India reduced barriers to capital goods imports that resulted in a 20 percent fall in the relative price of capital between 1990 and 2005. This led to a surge in capital goods imports and consequently the investment rate increased by 1.5 times during the same time period. After the Great Depression, Argentina restricted imports of capital goods. From the late 1930s to the late 1940s, the relative price of capital doubled and the investment rate declined.

Two remarks are in order regarding the counterfactual with zero trade barriers. (1) Iceberg costs. Part of the increases in income per worker are due to a mechanical implication of iceberg-type trade barriers. Reduction in trade barriers imply that less tradable resources melt away in the ocean during transit. For instance, country i pays country j for τ_{eij} units of capital goods but receives only one unit; $\tau_{eij} - 1$ units melt away in transit. Some of the increases in income per worker stem from simply recouping the lost resources. (2) Technology vs. Policy. Recall that we inferred the benchmark trade barriers using equation (4) and data on prices and trade flows. Such barriers could contain technology as well as policy components, so the reduction in barriers might not be achieved purely via policy changes. In the next subsection, we decompose the quantitative implications of the reduction to zero trade barriers for income per worker.

4.1.1 Decompositions of the changes in income per worker

Iceberg costs To quantify the increases in income from recouping the lost resources, we perform a "scuba diving" exercise: We hold the trade flows fixed and let the importing countries to recoup all of the capital goods and intermediate goods that were lost in transit in the ocean. We then compute the increase in the amount of final good using the increases in capital goods and intermediate goods but restricting them to be allocated across sectors in the same proportion as in the benchmark. Since, in our model, consumption (final good) is proportional to income per worker, this calculation helps us quantify the misallocation.

The total quantity of intermediate goods available to country i then is $\hat{M}_i = \sum_j M_i \pi_{mij} \tau_{mij}$. The quantity of capital goods available is $\hat{x}_i^e = \sum_j x_i^e \pi_{eij} \tau_{eij}$, so the steady state stock of producer durables is $\hat{k}_i^e = \hat{x}_i^e$. Under the restriction that in each country the intermediate goods and stock of producer durables are allocated across sectors in the same proportion as in the benchmark, the shares in the final good production are: $\hat{M}_{fi}/\hat{M}_i = M_{fi}/M_i$ and $\hat{k}_{fi}^e/\hat{k}_i^e = k_{fi}^e/k_i^e$. Final good consumption is $\hat{c}_{fi} = A_{fi} \left[\left((\hat{k}_{fi}^e)^{\mu} (k_{fi}^s)^{1-\mu} \right)^{\alpha} \ell_{fi}^{1-\alpha} \right]^{\nu_f} \hat{M}_{fi}^{1-\nu_f}$. Note that we have included only the direct effects of more intermediate goods and capital goods on the final good and excluded the indirect effects (e.g., more intermediate goods and capital goods would imply a higher stock of structures, and hence, more final good).

In country i, let $\hat{y}_i$ denote the income per worker (proportional to final good) from the above calculation and y_i^{free} denote the income per worker in the counterfactual economy with zero barriers. Write the increase in income due to zero barriers as $\frac{y_i^{free}-y_i}{y_i} = \frac{y_i^{free}-\hat{y}_i+\hat{y}_i-y_i}{y_i}$. Then $\frac{\hat{y}_i-y_i}{y_i^{free}-y_i}$ is a fraction of the increase that stems purely from recovering the tradable goods lost in the ocean. On average, this fraction is less than 3 percent.

On the other extreme, suppose we remove the proportionality restriction and allocate *all* of the recovered capital goods and intermediate goods to the final goods sector i.e., $\hat{M}_{fi} = M_{fi} + (\hat{M}_i - M_i)$ and $\hat{k}^e_{fi} = k^e_{fi} + (\hat{k}^e_i - k^e_i)$, where $\hat{M}_i - M_i$ is the recovered quantity of intermediate goods and $\hat{k}^e_i - k^e_i$ is the recovered quantity of capital goods. Then, calculating the gain as above, the increase in income as a fraction of that from eliminating all trade barriers is only 9 percent, on average.

Technology vs. Policy Suppose that every country had the same trade barrier as the U.S. That is, we imagine an admittedly extreme scenario that the U.S. trade barrier is entirely technological. To operationalize this thought experiment, we compute the average trade-weighted export barrier for the US in each sector: $\bar{\tau} = \sum_{i \neq US} \tau_{iUS} X_{iUS}/(I-1)$, where X_{iUS} are exports from the US to country i. This computation yields a capital goods trade barrier to every bilateral pair, $\tau_{eij} = \bar{\tau_e} = 1.77$, and an intermediate goods trade barrier, $\tau_{mij} = \bar{\tau_m} = 2.17$. With these trade barriers, the income gap between countries in the top and bottom deciles of the income distribution falls from 22.5 to 10.8. Recall that in the counterfactual with zero barriers the gap declined from 22.5 to 10.2, so reducing the barriers to the U.S. level achieves almost the same results as completely eliminating the barriers.

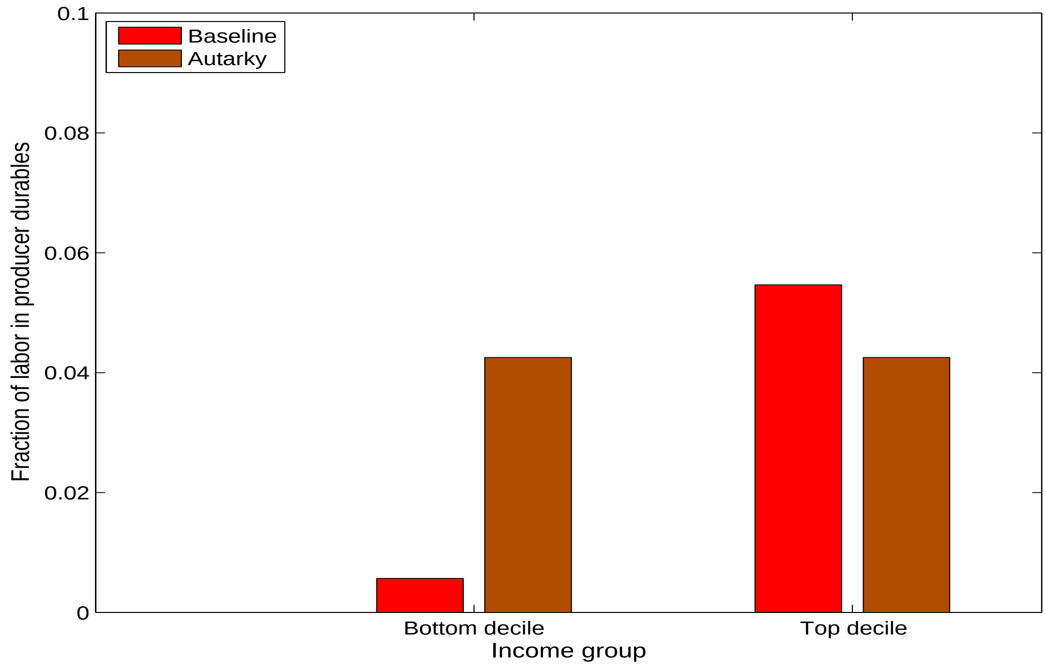
4.2 The role of capital goods trade

Capital goods trade affects cross-country differences in income per worker in our model through two channels: (i) capital per worker, since capital stock in each country is partly a result of the trade (π_{eii} in equation (2) affects k_i), and (ii) TFP, since the trade balance condition connects capital goods trade with intermediate goods trade and the home trade share in intermediate goods, π_{mii}, affects measured TFP in equation (1). To understand the quantitative role of capital goods trade, we conduct two counterfactual experiments: (i) we eliminate all trade in capital goods by setting τ_{eij} to prohibitively high levels for all country pairs and (ii) we eliminate all barriers to capital goods trade by setting τ_{eij} equal to 1. In both experiments, we leave all other parameters at their calibrated values; specifically, the intermediate goods trade barriers remain at the benchmark levels.

Autarky in capital goods In the benchmark case, poor countries are net exporters of intermediate goods and net importers of capital goods. Once capital goods trade is shut down, all countries trade only in intermediate goods, so the trade balance condition implies that exports of intermediate goods must equal the imports of intermediate goods in each country. This distorts the world pattern of capital goods production toward countries that do not have a comparative advantage in producing them i.e., the poor countries.

Figure 8 shows the fraction of labor employed in capital goods production in the top and bottom income deciles. Eliminating trade in capital goods forces poor countries to allocate over seven times more labor toward capital goods production, relative to the benchmark. Conversely, rich countries allocate 20 percent less labor toward capital goods production.

Figure 8: Fraction of labor used in capital goods production: benchmark and autarky in capital goods



With countries diverting resources away from their sector of comparative advantage, the world GDP shrinks by more than 6 percent. In each country, almost all of the decline in income per worker is due to decreased capital per worker. Again, capital being an endogenous factor of production is quantitatively important for the result.

Countries in the bottom decile suffer an income loss of 17 percent, on average. Without access to capital goods from rich countries, some poor countries suffer a greater loss: The income in Bolivia, for instance, declines by 30 percent. Again, the relative price of capital plays a key role. In our benchmark, Bolivia gets 24 units of capital goods for every unit of consumption, but with no trade in capital goods Bolivia gets only 11 units. As a result, Bolivia's investment rate declines by more than half and its steady state capital per worker declines by two-thirds.

Zero barriers in capital goods trade In this experiment, the income gap between countries in the top and bottom deciles of the income distribution falls to 18.2 (from 22.5 in the benchmark). Almost 95 percent of the reduction in the income gap stems from changes in capital per worker. The ratio of capital stock per worker, between countries in the top and bottom deciles of the income distribution, falls from 52 to 37 while the gap in the endogenous component of TFP declines only by 2 basis points.

With zero barriers to capital goods trade, poor countries increase their capital per worker relative to rich countries. This is driven by an increase in the investment rate, which in turn is driven by a decline in the relative price of producer durables. The channel through which trade barriers affect relative prices is discussed in Sposi (2013). Removal of barriers results in more specialization in the direction of comparative advantage, thereby increasing the average productivity in capital goods and intermediate goods sectors. This increased productivity implies higher prices of nontradables, i.e., final goods. Since poor countries have larger barriers, the prices of final goods in poor countries increase relative to rich countries. Meanwhile, there is no substantial change in the price of producer durables since they were roughly equal across countries even with the benchmark barriers. So the relative price of producer durables declines more in poor countries relative to rich countries and, hence, the aggregate investment rate increases more in poor countries than in rich countries. In the benchmark model the aggregate investment rate in rich countries is 2.22 times that in poor countries; with zero barriers in capital goods trade this ratio is 1.56.

Eaton and Kortum (2001) quantify the role of capital goods trade barriers in accounting for cross-country income differences using the neoclassical growth framework. As noted in Section 2.5, income per worker in the neoclassical growth model is $y = Z^{\frac{1}{1-\alpha}} \left(\frac{k}{y}\right)^{\frac{\alpha}{1-\alpha}} = Z^{\frac{1}{1-\alpha}} \left(\left(\frac{k^e}{y}\right)^{\mu} \left(\frac{k^s}{y}\right)^{1-\mu}\right)^{\frac{\alpha}{1-\alpha}}$. In steady state, for each sector $b \in \{e, s\}$, $\frac{k^b}{y} \propto \frac{x^b}{y}$ and $\frac{x^b}{y} \propto \frac{P_b x^b}{P_f y}\frac{P_f}{P_b}$. Since the investment rates measured in domestic prices, $\frac{P_b x^b}{P_f y}$, are constant across countries, the income per worker is proportional to the inverse of the product of relative price of capital and relative price of structures. Eaton and Kortum (2001) construct a trade-based relative price of capital where P_e is derived from coefficients in a gravity regression, and P_f and P_s are taken directly from the Penn World Tables. By design, capital goods trade barriers affect the relative price of capital in their model only through the changes in the absolute price of capital since they hold fixed the price of final goods. In our model, removing capital goods trade barriers affects mainly the price of the final good. In addition, in our model the trade barriers affect the price of structures, which is exogenous in Eaton and

Kortum (2001). Lastly, as noted by Hsieh and Klenow (2007), the trade-based measure of P_e is negatively correlated with economic development whereas in the data P_e is practically uncorrelated with economic development.

In Hsieh and Klenow (2007), eliminating capital goods trade barriers has no effect on the investment rate in poor countries relative to rich countries for two reasons. First, since the inferred capital goods trade barriers are no different in poor countries than in rich countries, a removal of these barriers has essentially no effect on the *difference* in the absolute price of capital between rich and poor countries. Second, the trade barriers in their model do not affect the price of the final consumption good. As a result, removing barriers to trade in capital goods does not alter the cross-country differences in relative price of capital and, hence, does not affect the cross-country differences in investment rates. In our model, removal of capital goods trade barriers leads to an equalization of the price of capital across countries and to an increase in the price of final goods in poor countries relative to rich countries. The resulting decline in the relative price of capital in poor countries leads to an increase in their investment rates relative to the investment rates in rich countries.

5 Conclusion

In this paper, we embed a multi country, multi sector Ricardian model of trade into a neoclassical growth framework. By calibrating our model to bilateral trade shares, relative prices, and income per worker, we match several trade and development facts within a unified framework. Our model is consistent with the world distribution of capital goods production, cross-country differences in investment rate and price of final goods, and cross-country equalization of price of capital goods and marginal product of capital. We also reproduce the cross-country patterns in capital per worker and home trade shares.

Trade barriers in our model imply a substantial misallocation of resources relative to the optimal allocation: Poor countries produce too much capital goods, while rich countries produce too little. Poor countries gain about two and a half times as much as rich countries do in the optimal allocation without any barriers to trade. Cross-country income differences decline by more than 50 percent when we switch to a world with zero trade barriers. Autarky in capital goods is costly for poor countries; They suffer an income loss of 17 percent.

Changes in trade barriers affect in income in our model predominantly through changes in capital stock. This channel is quantitatively important relative to the effect of trade barriers on TFP.

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APPENDICES

A Derivations

In this section we show how to derive analytical expressions for price indices and trade shares. Our derivations rely on three properties of the exponential distribution.

(i) $u \sim \exp(\mu)$ and $k > 0 \Rightarrow ku \sim \exp(\mu/k)$.

(ii) $u_1 \sim \exp(\mu_1)$ and $u_2 \sim \exp(\mu_2) \Rightarrow \min\{u_1, u_2\} \sim \exp(\mu_1 + \mu_2)$.

(iii) $u_1 \sim \exp(\mu_1)$ and $u_2 \sim \exp(\mu_2) \Rightarrow \Pr(u_1 \leq u_2) = \frac{\mu_1}{\mu_1+\mu_2}$.

A.1 Price indices

Here we derive the price index for intermediate goods, P_{mi}. The price index for capital goods can be derived in a similar manner. We denote the unit cost of an input bundle used in sector m by d_{mi}.

Perfect competition implies that the price in country i of the individual intermediate good u, when purchased from country j, equals unit cost in country j times the trade barrier: $p_{mij}(u) = B_m d_{mj} \tau_{mij} u_j^{\theta}$, where B_m is a collection of constant terms. International trade implies that country i purchases intermediate good u from the least-cost supplier, so the price of good u in country i is given by

$$p_{mi}(u)^{1/\theta} = (B_m)^{1/\theta} \min_j \left[(d_{mj}\tau_{mij})^{1/\theta} u_j \right].$$

Since $u_j \sim \exp(\lambda_{mj})$, it follows from property (i) that

$$(d_{mj}\tau_{mij})^{1/\theta} u_j \sim \exp\left((d_{mj}\tau_{mij})^{-1/\theta} \lambda_{mj} \right).$$

Then, property 2 implies that

$$\min_j \left[(d_{mj}\tau_{mij})^{1/\theta} u_j \right] \sim \exp\left(\sum_j (d_{mj}\tau_{mij})^{-1/\theta} \lambda_{mj} \right).$$

Lastly, appealing to property 1 again,

$$p_{mi}(u)^{1/\theta} \sim \exp\left(B_m^{-1/\theta} \sum_j (d_{mj}\tau_{mij})^{-1/\theta} \lambda_{mj} \right). \tag{A.1}$$

Let $\mu_{mi} = (B_m)^{-1/\theta} \sum_j (d_{mj}\tau_{mij})^{-1/\theta} \lambda_{mj}$. Then $P_{mi}^{1-\eta} = \mu_{mi} \int t^{\theta(1-\eta)} \exp(-\mu_{mi} t)\, dt$. Apply a change of variables so that $\omega_i = \mu_{mi} t$ and obtain

$$P_{mi}^{1-\eta} = (\mu_{mi})^{\theta(\eta-1)} \int \omega_i^{\theta(1-\eta)} \exp(-\omega_i) d\omega_i.$$

Let $\gamma = \Gamma(1+\theta(1-\eta))^{1/(1-\eta)}$, where $\Gamma(\cdot)$ is the gamma function. Therefore,

$$P_{mi} = \gamma (\mu_{mi})^{-\theta} = \gamma B_m \left[\sum_j (d_{mj}\tau_{mij})^{-1/\theta} \lambda_{mj} \right]^{-\theta}. \tag{A.2}$$

A.2 Trade shares

We now derive the trade shares π_{mij}, the fraction of country i's total spending on intermediate goods that was obtained from country j. Due to the law of large numbers, the fraction of good u that i obtains from j is also the probability that country j is the least-cost supplier of u:

$$\pi_{mij} = \Pr\left\{ p_{mij}(u) \leq \min_l [p_{mil}(u)] \right\} = \frac{(d_{mj}\tau_{mij})^{-1/\theta}\lambda_{mj}}{\sum_l (d_{ml}\tau_{mil})^{-1/\theta}\lambda_{ml}}, \tag{A.3}$$

where we have used equation (A.1) along with properties (ii) and (iii). Trade shares in the capital goods sector are derived identically.

A.3 Relative prices

Here we derive equations for three relative prices: P_{ei}/P_{fi}, P_{mi}/P_{fi}, and P_{si}/P_{fi}. Equations (A.2) and (A.3) imply that

$$\begin{aligned} \pi_{mii} &= \frac{d_{mi}^{-1/\theta}\lambda_{mi}}{(\gamma B_m)^{1/\theta} P_{mi}^{-1/\theta}} \\ \Rightarrow P_{mi} &\propto \frac{\left(\frac{r_i}{w_i}\right)^{\alpha\nu_m} \left(\frac{w_i}{P_{mi}}\right)^{\nu_m} P_{mi}}{\left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\theta}}, \end{aligned}$$

which implies that $\frac{w_i}{P_{mi}} \propto \left(\frac{w_i}{r_i}\right)^{\alpha} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\theta/\nu_m}$. Similarly,

$$P_{ei} \propto \frac{\left(\frac{r_i}{w_i}\right)^{\alpha\nu_e} \left(\frac{w_i}{P_{mi}}\right)^{\nu_e} P_{mi}}{\left(\frac{\lambda_{ei}}{\pi_{eii}}\right)^{\theta}}, \quad P_{si} \propto \frac{\left(\frac{r_i}{w_i}\right)^{\alpha\nu_s} \left(\frac{w_i}{P_{mi}}\right)^{\nu_s} P_{mi}}{1}, \quad P_{fi} \propto \frac{\left(\frac{r_i}{w_i}\right)^{\alpha\nu_f} \left(\frac{w_i}{P_{mi}}\right)^{\nu_f} P_{mi}}{A_{fi}}.$$

We show how to solve for P_{ei}/P_{fi}, and the other relative prices are solved for analogously. Taking ratios of the expressions above and substituting for w_i/P_{mi} we get

$$\begin{aligned}
\frac{P_{ei}}{P_{fi}} &\propto \left(\frac{r_i}{w_i}\right)^{\alpha(\nu_e-\nu_f)} \left(\frac{w_i}{P_{mi}}\right)^{\nu_e-\nu_f} \frac{A_{fi}}{(\lambda_{ei}/\pi_{eii})^{\theta}} \\
&= \frac{A_{fi}}{(\lambda_{ei}/\pi_{eii})^{\theta}} \left(\frac{r_i}{w_i}\right)^{\alpha(\nu_e-\nu_f)} \left[\left(\frac{w_i}{r_i}\right)^{\alpha} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\theta/\nu_m}\right]^{\nu_e-\nu_f} \\
&= \frac{A_{fi}}{(\lambda_{ei}/\pi_{eii})^{\theta}} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta(\nu_e-\nu_f)}{\nu_m}}.
\end{aligned}$$

Similarly,

$$\frac{P_{mi}}{P_{fi}} \propto \frac{A_{fi}}{(\lambda_{mi}/\pi_{mii})^{\theta}} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta(\nu_m-\nu_f)}{\nu_m}} \quad \text{and} \quad \frac{P_{si}}{P_{fi}} \propto \frac{A_{fi}}{1} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta(\nu_s-\nu_f)}{\nu_m}}.$$

A.4 Price and quantity of aggregate investment

First, we introduce an aggregate investment good in each country i, x_i, and a corresponding price index, P_{xi}, such that total investment expenditures is $P_{xi}x_i = P_{ei}x_i^e + P_{si}x_i^s$. This requires us to construct a depreciation rate, δ_x, for the aggregate investment good. Recall that the composite capital stock is a Cobb-Douglas aggregate of producer durables and structures: $k = (k^e)^{\mu}(k^s)^{1-\mu}$. The rental rate for the composite capital is then given by $r_x = \left(\frac{r_e}{\mu}\right)^{\mu}\left(\frac{r_s}{1-\mu}\right)^{1-\mu}$. No-arbitrage implies that $P_b = \frac{r_b}{\frac{1}{\beta}-(1-\delta_b)}$ for $b \in \{e, s\}$. An identical relationship holds for aggregate investment as well. Finally, in steady state, investments in each type of capital are such that the stocks of each type of capital are constant over time: $x^b = \delta_b k^b$ for $b \in \{e, s\}$. We impose an identical condition for aggregate investment.

In sum, we have three equations to solve for three unknowns: P_x, x, and δ_x.

$$P_x x = P_e x^e + P_s x^s \tag{A.4}$$

$$P_x = \frac{r_x}{\frac{1}{\beta} - (1-\delta_x)} \tag{A.5}$$

$$x^k = \delta_x k \tag{A.6}$$

Investment spending on each type of capital is $P_b x^b = \frac{\delta_b}{\frac{1}{\beta}-(1-\delta_b)} r_b k^b$, denoted by $\phi_b r_b k^b$. This can be further simplified to $P_e x^e = \mu\phi_e r_x k$ and $P_s x^s = (1-\mu)\phi_s r_x k$. Therefore, total investment spending from equation (A.4) is given by $P_x x = (\mu\phi_e + (1-\mu)\phi_s) r_x k = \phi_x r_x k$.

Next, combine equations (A.5) and (A.6) to get

$$P_x x = \frac{\delta_x}{\frac{1}{\beta} - (1-\delta_x)} r_x k.$$

The last two expressions imply that $\phi_x = \frac{\delta_x}{\frac{1}{\beta}-(1-\delta_x)}$, so $\delta_x = \frac{(1-\beta)\phi_x}{\beta(1-\phi_x)}$. Then we use equations (A.5) and (A.6) to solve for the price and quantity of aggregate investment since the equilibrium r and k are already determined.

A.5 Capital stock

Since $r_i k_i = \frac{\alpha}{1-\alpha} w_i$, aggregate stock of capital per worker $k_i \propto \frac{w_i}{r_i} = \frac{w_i}{r_{ei}^{\mu} r_{si}^{1-\mu}} \propto \left(\frac{w_i}{P_{ei}}\right)^{\mu} \left(\frac{w_i}{P_{si}}\right)^{1-\mu}$ ($r_{ei} \propto P_{ei}$ and $r_{si} \propto P_{si}$ come from the Euler equations). We derive w_i/P_{ei} by making use of the relative prices above:

$$\frac{w_i}{P_{ei}} = \frac{w_i}{P_{mi}} \frac{P_{mi}}{P_{ei}} \propto \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta}{\nu_m}} \left(\frac{w_i}{r_i}\right)^{\alpha} \frac{(\lambda_{ei}/\pi_{eii})^{\theta}}{(\lambda_{mi}/\pi_{mii})^{\theta}} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta(\nu_m-\nu_e)}{\nu_m}}.$$

Analogously,

$$\frac{w_i}{P_{si}} \propto \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta}{\nu_m}} \left(\frac{w_i}{r_i}\right)^{\alpha} \frac{1}{(\lambda_{mi}/\pi_{mii})^{\theta}} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta(\nu_m-\nu_s)}{\nu_m}}.$$

Again, use the fact that $k_i \propto \frac{w_i}{r_i}$ and then

$$\begin{aligned} k_i &\propto \left(\left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta}{\nu_m}} k_i^{\alpha} \frac{(\lambda_{ei}/\pi_{eii})^{\theta}}{(\lambda_{mi}/\pi_{mii})^{\theta}} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta(\nu_m-\nu_e)}{\nu_m}}\right)^{\mu} \\ &\times \left(\left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta}{\nu_m}} k_i^{\alpha} \frac{1}{(\lambda_{mi}/\pi_{mii})^{\theta}} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta(\nu_m-\nu_s)}{\nu_m}}\right)^{1-\mu} \\ \Rightarrow k_i &\propto \left(\left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta}{\nu_m}} \frac{(\lambda_{ei}/\pi_{eii})^{\theta}}{(\lambda_{mi}/\pi_{mii})^{\theta}} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta(\nu_m-\nu_e)}{\nu_m}}\right)^{\frac{\mu}{1-\alpha}} \\ &\times \left(\left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta}{\nu_m}} \frac{1}{(\lambda_{mi}/\pi_{mii})^{\theta}} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta(\nu_m-\nu_s)}{\nu_m}}\right)^{\frac{1-\mu}{1-\alpha}}. \end{aligned}$$

To derive an expression for the capital-output ratio, note that investment rates at domestic prices are identical across countries in our model: $\frac{P_{ei} x_i^e}{P_{fi} y_i}$ is a constant; similarly, $\frac{P_{si} x_i^s}{P_{fi} y_i}$ is also a constant. Therefore, $x_i^e/y_i \propto P_{fi}/P_{ei}$ and $x_i^s/y_i \propto P_{fi}/P_{si}$. To solve for the capital-output ratio write $k_i = (k_i^e)^{\mu}(k_i^s)^{1-\mu}$ in terms of relative price as follows: $k_i^e \propto x_i^e, k_i^s \propto x_i^s$, $x_i^e/y_i \propto P_{fi}/P_{ei}$, and $x_i^s/y_i \propto P_{fi}/P_{si}$. Finally, use the expressions for relative prices in terms of $A_{fi}, \lambda_{ei}, \lambda_{si}, \pi_{eii}$, and π_{mii} given in Appendix A.3.

$$\frac{k_i}{y_i} \propto \left(\frac{A_{fi}}{(\lambda_{ei}/\pi_{eii})^{\theta}} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta(\nu_e-\nu_f)}{\nu_m}}\right)^{-\mu} \left(\frac{A_{fi}}{1} \left(\frac{\lambda_{mi}}{\pi_{mii}}\right)^{\frac{\theta(\nu_s-\nu_f)}{\nu_m}}\right)^{\mu-1}.$$

A.6 Real MPK equalization across countries

We make the argument for the marginal product of producer durables capital; the argument for the marginal product of structures capital is identical. First, consider the marginal product of producer durables in the intermediate goods sector. Suppose country i is producing a positive amount of the individual intermediate good u; then the marginal product of producer durables capital for producing intermediate good u is

$$MPK^e_{mi}(u) = \alpha\nu_m\mu k^e_{mi}(u)^{\alpha\nu_m\mu-1}k^s_{mi}(u)^{\alpha\nu_m(1-\mu)}l(u)^{(1-\alpha)\nu_m}M_{mi}(u)^{1-\nu_m} = \alpha\nu_m\mu\frac{m_i(u)}{k^e_{mi}(u)},$$

where $m_i(u)$ is the quantity per worker in country i. Thus, the value of the marginal product of producer durables for u is

$$VMPK^e_{mi}(u) \equiv p_{mi}(u)MPK^e_{mi}(u) = \alpha\nu_m\mu\,\frac{p_{mi}(u)m_i(u)}{k^e_{mi}(u)},$$

where $p_{mi}(u)$ is the price of intermediate good u. Due to perfect competition, the Cobb-Douglas specifications for technologies, as well as perfect mobility of factors across all sectors within the country, the compensation to producer durables capital is

$$r_{ei}k^e_{mi}(u) = \alpha\nu_m\mu\, p_{mi}(u)m_i(u).$$

Combining the last two expressions it is clear that the value of the marginal product of producer durables is identical across all intermediate goods – that is, $VMPK^e_{mi}(u) = r_{ei}$ for all u produced in country i. Integrating over the continuum in the intermediate goods sector, we get $L_i r_{ei} k^e_{mi} = \alpha\nu_m\mu Y_{mi}$. Dividing both sides by the price of producer durables and rearranging, we obtain

$$\frac{r_{ei}}{P_{ei}} = \alpha\nu_m\mu\frac{Y_{mi}}{L_i P_{ei} k^e_{mi}},$$

A similar logic holds for the other sectors as well: For each sector $b \in \{e, s, m, f\}$,

$$\frac{r_{ei}}{P_{ei}} = \alpha\nu_b\mu\frac{Y_{bi}}{L_i P_{ei} k^e_{bi}},$$

where the right-hand side is the real value of the marginal product of producer durables in any sector b.

Recall that the Euler equation implies that $\frac{r_{ei}}{P_{ei}} = \frac{1+g}{\beta} - (1-\delta_e)$. Therefore, the real rate of return on producer durables capital is $R^\star = 1 + r_{ei}/P_{ei} - \delta_e = (1+g)/\beta$ which is common to all countries. The same result applies to the real rate of return on structures capital as well – that is, $R^\star = 1 + r_{si}/P_{si} - \delta_s = (1+g)/\beta$.

B Data

This section describes our data sources and how we map our model to the data.

Categories Capital goods in our model corresponds to "Machinery & equipment" categories in the ICP (http://siteresources.worldbank.org/ICPEXT/Resources/ICP_2011.html). We identify the categories according to the two-digit ISIC classification (for a complete list go to http://unstats.un.org/unsd/cr/registry/regcst.asp?cl=2). The ISIC categories for capital goods are 29 through 35. Intermediate goods are identified as all of manufacturing categories 15 through 37 excluding those identified as capital goods. Structures in our model corresponds to ISIC category 45 labeled "Construction."Final goods in our model correspond to the remaining ISIC categories excluding capital goods, intermediate goods, and structures.

Prices Data on the prices of capital goods across countries are constructed by the ICP (available at http://siteresources.worldbank.org/ICPEXT/Resources/ICP_2011.html). We use the variable PPP price of "Machinery & equipment", world price = 1. We take the price of structures also from the ICP; we use the variable PPP price of "Construction", world price = 1. The price of final goods in our model is the price of consumption goods from PWT63, `PC`. The price of intermediate goods is constructed by aggregating prices of goods across various subsectors within intermediate goods using data from the ICP. For each country, we have two pieces of information on each good in the intermediate goods basket: (i) expenditure in domestic currency converted to U.S. dollars using the exchange rate and (ii) expenditure in international dollars (PPP). We sum the exchange-rate-adjusted expenditures in domestic currency, and divide that value by the sum of expenditures in international dollars to compute the price. In fact, the prices of capital goods and structures are computed exactly the same way in the ICP.

National accounts PPP income per worker is from PWT63, variable `RGDPWOK`. The size of the workforce is recovered from other variables in PWT63: number of workers = 1000*`POP`*`RGDPL`/`RGDPWOK`. In constructing aggregate stocks of capital, we follow the perpetual inventory method used by Caselli (2005):

$$K_{t+1} = I_t + (1 - \delta)K_t,$$

where I_t is aggregate investment in PPP and δ is the depreciation rate. I_t is computed from PWT63 as `RGDPL*POP*KI`. The initial capital stock K_0 is computed as $I_0/(g + \delta)$, where I_0 is the value of the investment series in the first year it is available, and g is the average geometric growth rate for the investment series between the first year with available data and 1975.[5] Following the literature, δ is set to 0.06.

Production Data on manufacturing production are from INDSTAT2, a database maintained by UNIDO (2013) at the two-digit level, ISIC revision 3. We aggregate the four-digit categories into either capital goods or intermediate goods using the classification method discussed above. Data for most countries are from the year 2005, but for some countries that have no available data for 2005, we look at the years 2002, 2003, 2004, and 2006 and take data from the year closest to 2005 for which they are available. We then convert the data into 2005 values by using growth rates of total manufacturing output over the same period.

Trade flows Data on bilateral trade flows are obtained from the UN Comtrade database for the year 2005 (http://comtrade.un.org/). All trade flow data are at the four-digit level, SITC revision 2, and are aggregated into respective categories as either intermediate goods or capital goods. In order to link trade data to production data we use the correspondence provided by Affendy, Sim Yee, and Satoru (2010), which links ISIC revision 3 to SITC revision 2.

Construction of trade shares The empirical counterpart to the model variable π_{mij} is constructed following Bernard et al. (2003) (recall that this is the fraction of country i's spending on intermediate goods produced in country j). We divide the value of country i's imports of intermediates from country j by i's gross production of intermediates minus i's total exports of intermediates (for the whole world) plus i's total imports of intermediates (for only the sample) to arrive at the bilateral trade share. Trade shares for the capital goods sector are obtained similarly.

[5] For some countries the first year with available data is after 1975. In such cases, we calculate the geometric growth rate for first the 5 years with available data.

C Estimation of θ

Simonovska and Waugh (2014) build on the procedure in Eaton and Kortum (2002). We refer to these papers as SW and EK henceforth. We briefly describe EK's method before explaining SW's method. For now we ignore sector subscripts, as θ for each sector is estimated independently.

In our model (equation (4)),

$$\log\left(\frac{\pi_{ij}}{\pi_{jj}}\right) = -\frac{1}{\theta}(\log \tau_{ij} - \log P_i + \log P_j) \tag{C.7}$$

where P_i and P_j denote the aggregate prices in countries i and j for the sector under consideration. If we knew τ_{ij}, it would be straightforward to estimate θ, but we do not. A key element is to exploit cross-country data on disaggregate prices of goods within the sector.

Let x denote a particular good in the continuum. Each country i faces a price, $p_i(x)$, for that good. Ignoring the source of the producer of good x, a simple no-arbitrage argument implies that, for any two counties i and j, $\frac{p_i(x)}{p_j(x)} \leq \tau_{ij}$. Thus, the gap in prices between any two countries provides a lower bound for the trade barrier between them. In our model, we assume that the same bilateral barrier applies to all goods in the continuum, so $\max\limits_{x\in X}\{\frac{p_i(x)}{p_j(x)}\} \leq \tau_{ij}$, where X denotes the set of goods for which disaggregate prices are available. One could thus obtain the bilateral trade barrier as $\log \hat{\tau}_{ij}(X) = \max_{x\in X}\{\log p_i(x) - \log p_j(x)\}$.

EK derive a method of moments estimator, $\frac{1}{\hat{\rho}_{EK}}$, as:

$$\frac{1}{\hat{\rho}_{EK}} = -\frac{\sum_i \sum_j \log\left(\frac{\pi_{ij}}{\pi_{jj}}\right)}{\sum_i \sum_j [\log \hat{\tau}_{ij}(X) - \log \hat{P}_i(X) + \log \hat{P}_j(X)]}, \tag{C.8}$$

where $\log \hat{P}_i(X) = \frac{1}{|X|} \sum\limits_{x\in X} \log p_i(x)$ is the average price of goods in X in country i and $|X|$ is the number of goods in X.

SW show that the EK estimator is biased. This is because the sample of disaggregate prices is only a subset of all prices. Since the estimated trade barrier is only a lower bound to the true trade barrier, a smaller sample of prices leads to a lower estimate of $\hat{\tau}_{ij}$ and, hence, a higher estimate of $\frac{1}{\hat{\rho}_{EK}}$. SW propose a simulated method of moments estimator to correct for the bias.

The SW methodology is as follows. Start with an arbitrary value of θ. Simulate marginal costs for all countries for a large number of goods as a function of θ. Compute the bilateral trade shares π_{ij} and prices $p_i(x)$. Use a subset of the simulated prices and apply the EK methodology to obtain a biased estimate of θ, call it $\rho(\theta)$. Iterate on θ until $\hat{\rho}_{EK} = \rho(\theta)$ to uncover the true θ.

The first step is to parameterize the distribution from which marginal costs are drawn. This step requires exploiting the structure of the model. The model implies that

$$\log \frac{\pi_{ij}}{\pi_{ii}} = F_j - F_i - \frac{1}{\theta} \log(\tau_{ij}), \tag{C.9}$$

where $F_i \equiv \log d_i^{-1/\theta} \lambda_i$. The F_i governs the distribution of marginal costs in country i. In order to estimate these, SW use a parsimonious gravity specification for trade barriers:

$$\log \tau_{ij} = dist_k + brdr_{ij} + exj + \varepsilon_{ij}. \tag{C.10}$$

The coefficient $dist_k$ is the effect of distance between countries i and j lying in the kth distance interval.[6] The coefficient $brdr_{ij}$ is the effect of countries i and j having a shared border. The term ex_j is a country-specific exporter fixed effect. Finally, ε_{ij} is a residual that captures impediments to trade that are orthogonal to the other terms. Combining the gravity specification with equation C.9, SW use ordinary least squares to estimate F_i for each country and bilateral trade barriers for all countries.

The second step is to simulate prices for every good in the "continuum" in every country. Recall that $p_{ij}(x) = \tau_{ij} \frac{d_j}{z_j(x)}$, where z_j is country j's productivity. Instead of simulating these productivities, SW show how to simulate the inverse marginal costs, $imc_j = z_j(x)/d_j$. In particular, they show that the inverse marginal cost has the following distribution: $F(imc_i) = \exp(-\tilde{F}_i imc_i^{-1/\theta})$, where $\tilde{F}_i = \exp(F_i)$. They discretize the grid to 150,000 goods and simulate the inverse marginal costs for each good in each country. Combining the simulated inverse marginal costs with the estimated trade barriers, they find the least-cost supplier for every country and every good and then construct country-specific prices as well as bilateral trade shares.

The third step is to obtain a biased estimate of θ using the simulated prices. Choose X to be a subset of the 150,000 prices such that X contains the same number of disaggregate prices as in the data. Call that estimate $\frac{1}{\rho_s(\theta)}$. Then perform $s = 100$ simulations. Finally, choose a value for θ such that the average "biased" estimate of $\frac{1}{\theta}$ from simulated prices is sufficiently close to the biased estimate obtained from the observed prices – that is, $\frac{1}{100} \sum_s \rho_s(\theta) = \hat{\rho}_{EK}$.

One caveat is that the number of disaggregate price categories that fall under producer durables is small. Therefore, we also include consumer durables to expand the sample size.

[6] The distance intervals are measured in miles using the great circle method: [0,375); [375,750); [750,1500); [1500,3000); [3000,6000); and [6000,max).

D Calibrated productivity parameters

Table D.1: Productivity parameters

Country	**Isocode**	A_{fi}	λ_{ei}^{θ}	λ_{mi}^{θ}	$\left(\frac{\lambda_{ei}}{\lambda_{mi}}\right)^{\theta}$
Albania	ALB	0.29	1.25	4.18	0.30
Argentina	ARG	0.71	2.77	7.48	0.37
Armenia	ARM	0.58	0.89	4.63	0.19
Australia	AUS	0.90	8.20	9.24	0.89
Austria	AUT	0.91	7.48	7.93	0.94
Azerbaijan	AZE	0.42	1.81	1.27	1.42
Belarus	BLR	1.09	3.10	5.76	0.54
Belgium	BEL	0.93	3.40	6.81	0.50
Bolivia	BOL	0.32	0.55	4.82	0.11
Brazil	BRA	0.47	3.98	7.14	0.56
Bulgaria	BGR	0.48	2.73	6.10	0.45
Cameroon	CMR	0.32	2.54	4.84	0.53
Canada	CAN	0.89	7.55	8.02	0.94
Chile	CHL	0.81	3.38	7.78	0.43
China	CHN	0.43	3.50	5.39	0.65
Colombia	COL	0.46	2.61	6.13	0.43
Cyprus	CYP	0.75	4.06	7.28	0.56
Czech Republic	CZE	0.70	4.38	7.40	0.59
Denmark	DNK	0.79	6.06	7.75	0.78
Ecuador	ECU	0.37	2.78	5.39	0.52
Egypt	EGY	0.60	3.05	5.38	0.57
Estonia	EST	0.60	3.17	5.50	0.58
Ethiopia	ETH	0.17	0.58	2.87	0.20
Fiji	FJI	0.44	1.16	4.81	0.24
Finland	FIN	0.80	9.52	8.58	1.11
France	FRA	0.86	8.62	9.16	0.94
Georgia	GEO	0.46	1.46	1.90	0.77
Germany	GER	0.83	8.52	8.69	0.98
Ghana	GHA	0.21	1.01	3.55	0.28
Greece	GRC	0.86	5.67	8.37	0.68
Hong Kong	HKG	1.07	4.41	1.90	2.32
Hungary	HUN	0.69	3.93	7.36	0.53
Iceland	ISL	0.88	5.47	3.99	1.37
India	IND	0.33	3.18	5.53	0.58
Indonesia	IDN	0.40	1.47	4.87	0.30
Iran	IRN	0.67	3.98	1.72	2.32
Ireland	IRL	0.97	6.01	3.28	1.83
Italy	ITA	0.89	9.65	9.15	1.05
Japan	JPN	0.85	10.70	8.80	1.22
Jordan	JOR	0.43	3.49	5.93	0.59
Kazakhstan	KAZ	0.69	1.84	2.23	0.82
Kenya	KEN	0.25	1.55	4.09	0.38
Korea, Republic of	KOR	0.76	9.37	7.92	1.18
Kyrgyzstan	KGZ	0.41	0.92	4.33	0.21
Latvia	LVA	0.52	2.61	4.65	0.56
Lebanon	LBN	0.47	5.31	6.07	0.87
Lithuania	LTU	0.55	2.66	6.16	0.43
Luxembourg	LUX	1.15	5.33	4.39	1.21
Macao	MAC	1.13	3.94	3.86	1.02
Macedonia	MKD	0.41	2.75	5.57	0.49
Madagascar	MDG	0.13	0.85	1.38	0.61
Malawi	MWI	0.21	1.53	3.16	0.49
Malaysia	MYS	0.85	1.65	6.73	0.25
Malta	MLT	0.79	3.72	5.97	0.62
Mauritius	MUS	1.07	1.79	5.77	0.31
Mexico	MEX	0.53	2.40	7.21	0.33
Moldova	MDA	0.39	0.98	2.98	0.33
Mongolia	MNG	0.26	1.35	2.08	0.65
Morocco	MAR	0.48	2.66	4.79	0.55
Netherlands	NLD	0.83	3.76	6.65	0.56

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Table D.1 – Continued

Country	**Isocode**	A_{fi}	λ_{ei}^{θ}	λ_{mi}^{θ}	$\left(\frac{\lambda_{ei}}{\lambda_{mi}}\right)^{\theta}$
New Zealand	NZL	0.74	6.81	8.31	0.82
Pakistan	PAK	0.39	2.45	5.38	0.46
Paraguay	PRY	0.36	1.09	5.13	0.21
Peru	PER	0.35	2.55	6.38	0.40
Philippines	PHL	0.40	1.22	4.96	0.25
Poland	POL	0.56	4.49	7.49	0.60
Portugal	PRT	0.64	4.63	7.87	0.59
Romania	ROM	0.44	3.23	6.18	0.52
Russia	RUS	0.55	4.72	6.60	0.72
Senegal	SEN	0.23	1.28	3.70	0.34
Singapore	SGP	1.04	3.11	4.28	0.73
Slovak Republic	SVK	0.61	1.99	4.73	0.42
Slovenia	SVN	0.74	4.28	7.45	0.58
South Africa	ZAF	0.61	5.91	6.95	0.85
Spain	ESP	0.84	7.12	9.24	0.77
Sri Lanka	LKA	0.46	2.18	5.52	0.39
Sudan	SDN	0.23	2.57	4.53	0.57
Sweden	SWE	0.81	9.49	8.15	1.16
Tanzania	TZA	0.11	0.65	3.53	0.18
Thailand	THA	0.46	1.55	5.63	0.27
Trinidad and Tobago	TTO	0.80	2.45	2.32	1.06
Tunisia	TUN	0.73	3.26	5.44	0.60
Turkey	TUR	0.47	5.04	6.90	0.73
Ukraine	UKR	0.58	2.41	5.82	0.41
United Kingdom	GBR	0.84	8.90	8.56	1.04
United States	USA	1.00	10.00	10.00	1.00
Uruguay	URY	0.56	1.64	6.73	0.24
Vietnam	VNM	0.32	2.08	4.03	0.52