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Capital Accumulation and Dynamic Gains from Trade *

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Abstract

We compute welfare gains from trade in a dynamic, multicountry model with capital accumulation and trade imbalances. We develop a gradient-free method to compute the exact transition paths following a trade liberalization. We find that (i) larger countries accumulate a current account surplus, and financial resources flow from larger countries to smaller countries, boosting consumption in the latter, (ii) countries with larger short-run trade deficits accumulate capital faster, (iii) the gains are nonlinear in the reduction in trade costs, and (iv) capital accumulation accounts for substantial gains. The net foreign asset position before the liberalization is positively correlated with the gains. The tradables intensity in consumption goods production determines the static gains, and the tradables intensity in investment goods production determines the dynamic gains that include capital accumulation.

JEL codes: E22, F11, F62

Keywords: Welfare gains; Dynamics; Capital accumulation; Trade imbalances

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1 Introduction

How large are the welfare gains from trade? This is an old and important question. It has typically been answered in static settings by computing the change in real income from an observed equilibrium to a counterfactual equilibrium. In such computations, the factors of production and technology in each country are held fixed, and the change in real income is immediate and is entirely due to the change in each country's trade share that responds to a change in trade costs. Recent examples include Arkolakis, Costinot, and Rodríguez-Clare (2012) (ACR hereafter), who compute the welfare cost of autarky, and Waugh and Ravikumar (2016), who compute the welfare gains from frictionless trade.[1]

By design, the above computations cannot distinguish between static and dynamic gains. The static gains accrue immediately after a trade liberalization, and there is no cost to increasing consumption. Dynamic gains, on the other hand, accrue gradually. For instance, capital accumulation is costly because it requires forgone consumption. Consumption smoothing motives imply that capital accumulation is gradual.

We calculate welfare gains from trade in a dynamic, multicountry Ricardian model where international trade affects the capital stock in each country in each period. Our environment is a version of Eaton and Kortum (2002) embedded in a two-sector neoclassical growth model, similar to Alvarez (2017). There is a continuum of tradable intermediate goods that are used in the production of investment goods, final consumption goods, and intermediate goods. Each country is endowed with an initial stock of capital. Investment goods augment the stock of capital. We add two features that affect the gains: (i) cross-country heterogeneity in the tradables intensity in investment goods and in consumption goods and (ii) endogenous trade imbalances. The first feature affects the cross-country heterogeneity in the rate of capital accumulation after a trade liberalization and, hence, the gains from trade. The second feature helps each country smooth its consumption over time and, hence, affects the gains.

We calibrate the tradables intensity using the World Input-Output Database (WIOD). We calibrate productivities and trade costs so that the steady state of the model reproduces the observed bilateral trade flows across 44 countries and the trade imbalances in each country. We then conduct a counterfactual exercise in which there is an unanticipated, uniform, and permanent 20 percent reduction in trade costs in all countries. We compute the exact levels of endogenous variables along the transition path from the calibrated steady state to the counterfactual steady state and calculate the welfare gains using a consumption-

[1] See Adao, Costinot, and Donaldson (2017) for a nonparametric generalization of ACR.

equivalent measure as in Lucas (1987). Welfare gains from the trade liberalization accrue gradually in our model, and our measure of gains includes the entire transition path.

We find that (i) the current account balance immediately after the liberalization is positively correlated with size—larger countries accumulate a current account surplus, and financial resources flow from larger countries to smaller countries; (ii) the half-life for capital accumulation is negatively correlated with short-run trade deficits—countries with larger short-run trade deficits accumulate capital faster; (iii) gains from trade are nonlinear—the *elasticity* of gains with respect to reductions in trade costs is higher for larger reductions; (iv) dynamic gains are 80 percent of steady-state gains; and (v) dynamic gains are 35 percent more than static gains.

Trade liberalization affects the gains in our model through two channels: total factor productivity (TFP) and the capital-labor ratio. The TFP channel is a familiar one in trade models. Trade liberalization results in a decline in the home trade share and, hence, an increase in TFP, which increases output. This channel affects the level of consumption along the transition. Resources flow to countries that experience a larger increase in TFP. These countries run a current account deficit in the short run and use it to finance increases in consumption and investment that exceed increases in output. In general, small countries run current account deficits and large countries run current account surpluses in the short run. The current account dynamics imply that larger countries backload consumption, whereas smaller countries frontload consumption.

Trade liberalization also increases the rate of capital accumulation as higher TFP boosts the returns to capital. As a result, capital accumulates, yielding higher output and consumption along the transition path. The increase in the capital-labor ratio is gradual, as in the neoclassical growth model.[2] In addition, trade liberalization increases the rate of capital accumulation due to the decrease in the price of tradables. In our model, investment goods production is tradables intensive and higher intensity implies a larger response of the capital-labor ratio to trade liberalization. This channel also affects consumption along the transition path. In a static model, the capital-labor ratio channel is clearly absent.

The tradables intensity in each sector plays an important role in our model. After a trade liberalization, the tradables intensity in investment goods production determines the transition path for capital and has little effect on TFP dynamics, while the tradables intensity in consumption goods determines the transition path of TFP and has little effect on the

[2] In a two-country model with balanced trade, Connolly and Yi (2015) show that reductions in trade costs were quantitatively important for the *steady-state* capital stock and income in South Korea's growth miracle.

dynamics of capital. Furthermore, investment goods production is typically more tradables intensive than consumption goods production, and countries with a larger difference between the two intensities experience a larger decrease in the relative price of investment and a larger increase in the investment rate. This result is similar to the findings in Mutreja, Ravikumar, and Sposi (2018), who examine the role of this channel on economic development in a model where there is no cross-country heterogeneity in the intensities.

We provide a fast computational method for solving multicountry trade models with large state spaces. The state variables in our model include capital stocks as well as net foreign asset (NFA) positions. Our algorithm iterates on prices using excess demand equations and delivers the entire transition path for 44 countries in approximately 30 minutes on a standard computer (see also Alvarez and Lucas, 2007). Our algorithm uses gradient-free updating rules that are faster than the nonlinear solvers used in recent dynamic models of trade (e.g., Eaton, Kortum, Neiman, and Romalis, 2016; Kehoe, Ruhl, and Steinberg, 2018).

Our paper is related to three papers on multicountry models with capital accumulation: Alvarez (2017), Eaton, Kortum, Neiman, and Romalis (2016), and Anderson, Larch, and Yotov (2015).[3] In a model with period-by-period balanced trade, Alvarez (2017) approximates the dynamics by linearizing around the counterfactual steady state. Our computational method provides an exact dynamic path and is more accurate for computing transitional dynamics for large trade liberalizations. In addition, there is a propagation from trade imbalances to capital accumulation in our model: Countries with a trade deficit accumulate capital faster after a trade liberalization, and changes in current rates of capital accumulation affect future trade imbalances which, in turn, affect future rates of capital accumulation. Thus, the steady-state capital stock depends on the current account dynamics. Hence, similar to other models with trade imbalances, the counterfactual steady state cannot be determined independently from the initial steady state and transition.

Eaton, Kortum, Neiman, and Romalis (2016) examine the collapse of trade during the 2008 recession. They quantify the roles of different shocks via counterfactuals by solving the planner's problem, where the Pareto weight for each country is its share in world consumption expenditures and is the same in the benchmark and in the counterfactual. We solve for the competitive equilibrium and find that each country's consumption share changes in the counterfactual. For example, Bulgaria's share increases, whereas the U.S. share decreases.

[3]Baldwin (1992) and Brooks and Pujolas (2018) study welfare gains in two-country models with capital accumulation and balanced trade, while Alessandria, Choi, and Ruhl (2018) study the same in a two-country model with capital accumulation and trade imbalances. In Appendix F, we provide more details on two-country versus multicountry models.

Anderson, Larch, and Yotov (2015) compute transitional dynamics in a model where the investment rate does not depend on trade costs and can be computed once and for all as a constant pinned down by the structural parameters. The transition path can then be computed as a solution to a sequence of static problems. In our model, current allocations and prices depend on the entire path of prices and trade costs. Hence, we have to simultaneously solve a system of second-order, nonlinear difference equations. Empirically, Wacziarg and Welch (2008) show an increase in the investment rate after trade liberalizations for a sample of 118 countries, which is consistent with our model's implication.

The rest of the paper proceeds as follows. Section 2 presents the model. Section 3 describes the calibration, and Section 4 reports the results for counterfactuals. Section 5 explores the roles of capital accumulation and intensities of tradables. Section 6 concludes.

2 Model

There are I countries indexed by $i = 1, \ldots, I$, and time is discrete, running from $t = 1, \ldots, \infty$. There are three sectors: consumption, investment, and intermediates, denoted by c, x, and m, respectively. Consumption goods and investment goods are not tradable. There is a continuum of *intermediate varieties* that are tradable. Trade is subject to iceberg costs.

Each country has a representative household that owns the country's primary factors of production—capital and labor. Capital and labor are mobile across sectors within a country but are immobile across countries. The household inelastically supplies capital and labor to domestic firms and purchases consumption and investment goods from the domestic firms. Investment augments the stock of capital. Households can trade one-period bonds. There is no uncertainty, and households have perfect foresight. (In Appendix G, we enrich our model with more sectors and a complete input-output (IO) structure.)

In our notation below, country-specific parameters and variables have subscript i and the variables that vary over time have subscript t.

Endowments The representative household in country i is endowed with a labor force of size L_i in each period, an initial stock of capital, K_{i1}, and an initial NFA position, $\mathcal{A}_{i1}$.

2.1 Technology

There is a continuum of varieties in the intermediates sector. Each variety is tradable and is indexed by $v \in [0, 1]$. All of the varieties are combined with constant elasticity to construct a composite intermediate good:

$$M_{it} = \left[\int_0^1 q_{it}(v)^{1-1/\eta} dv\right]^{\eta/(\eta-1)},$$

where η is the elasticity of substitution between any two varieties. The term $q_{it}(v)$ is the quantity of variety v used by country i to construct the composite good at time t, and M_{it} is the quantity of the composite good available as input.

Varieties Each variety is produced using capital, labor, and the composite good. The technologies for producing each variety are given by

$$Y_{mit}(v) = z_{mi}(v) \left(K_{mit}(v)^{\alpha} L_{mit}(v)^{1-\alpha}\right)^{\nu_{mi}} M_{mit}(v)^{1-\nu_{mi}}.$$

The term $M_{mit}(v)$ denotes the quantity of the composite good used as an input to produce $Y_{mit}(v)$ units of variety v, while $K_{mit}(v)$ and $L_{mit}(v)$ denote the quantities of capital and labor used, respectively. The parameter $\nu_{mi} \in [0, 1]$ denotes the share of value added in total output, and α denotes capital's share in value added.

The term $z_{mi}(v)$ denotes country i's productivity for variety v. Following Eaton and Kortum (2002), the productivity draw comes from independent Fréchet distributions with shape parameter θ and country-specific scale parameter T_{mi}, for $i = 1, 2, \ldots, I$. The c.d.f. for productivity draws in country i is $F_{mi}(z) = \exp(-T_{mi} z^{-\theta})$.

Consumption good Each country produces a final consumption good using capital, labor, and intermediates according to

$$Y_{cit} = A_{ci} \left(K_{cit}^{\alpha} L_{cit}^{1-\alpha}\right)^{\nu_{ci}} M_{cit}^{1-\nu_{ci}}.$$

The terms K_{cit}, L_{cit}, and M_{cit} denote the quantities of capital, labor, and composite good, respectively, used to produce Y_{cit} units of consumption at time t. The parameter $1 - \nu_{ci}$ denotes the tradables intensity, and A_{ci} is the productivity in the consumption goods sector.

Investment good Each country produces an investment good using capital, labor, and intermediates according to

$$Y_{xit} = A_{xi} \left(K_{xit}^{\alpha} L_{xit}^{1-\alpha}\right)^{\nu_{xi}} M_{xit}^{1-\nu_{xi}}.$$

The terms K_{xit}, L_{xit}, and M_{xit} denote the quantities of capital, labor, and composite good, respectively, used to produce Y_{xit} units of investment. The parameter $1-\nu_{xi}$ is the tradables intensity, and A_{xi} is the productivity in the investment goods sector. When $\nu_{xi} < \nu_{ci}$, investment goods production is more tradables intensive than consumption goods production.

Capital accumulation The representative household enters period t with K_{it} units of capital, which depreciates at the rate δ. Investment, X_{it}, adds to the stock of capital subject to an adjustment cost:

$$K_{it+1} = (1-\delta)K_{it} + \delta^{1-\lambda} X_{it}^{\lambda} K_{it}^{1-\lambda},$$

where λ is the elasticity of capital accumulation with respect to investment. This specification ensures that in steady state there is no adjustment cost to replace depreciated capital (i.e., $X^\star = \delta K^\star$). For convenience, we work with investment:

$$X_{it} = \Phi(K_{it+1}, K_{it}) = \delta^{\frac{\lambda-1}{\lambda}} \left(K_{it+1} - (1-\delta)K_{it}\right)^{\frac{1}{\lambda}} K_{it}^{\frac{\lambda-1}{\lambda}}.$$

Net foreign asset accumulation The household can borrow or lend to the rest of the world by trading one-period bonds; let B_{it} denote the net purchases of bonds by country i and q_t denote the world interest rate on bonds at time t.[4] The representative household enters period t with an NFA position $\mathcal{A}_{it}$. If $\mathcal{A}_{it} < 0$, then country i is indebted at time t. The NFA position evolves according to

$$\mathcal{A}_{it+1} = \mathcal{A}_{it} + B_{it}.$$

We assume that all debts are eventually paid off. Countries that borrow in the short run to finance trade deficits will have to pay off the debts in the long run via perpetual trade surpluses. Each country's current account balance, B_{it}, equals net exports plus net foreign income on assets:

$$B_{it} = P_{mit}\left(Y_{mit} - M_{it}\right) + q_t \mathcal{A}_{it},$$

where $P_{mit} M_{it}$ is the total expenditure on intermediates including imported intermediates, and $P_{mit} Y_{mit}$ is total sales including exports.

[4]The adjustment cost specification implies that the household chooses a unique portfolio of bonds and capital since the rate of return on investment depends on the quantity of investment.

Budget constraint The representative household earns a rental rate r_{it} on capital and a wage rate w_{it} on labor. If the household has a positive NFA position at time t, then net-foreign income, $q_t\mathcal{A}_{it}$, is positive. Otherwise, resources are used to pay off existing liabilities. The household purchases consumption at the price P_{cit} and purchases investment at the price P_{xit}. The budget constraint is given by

$$P_{cit}C_{it} + P_{xit}X_{it} + B_{it} = r_{it}K_{it} + w_{it}L_i + q_t\mathcal{A}_{it}.$$

2.2 Trade

International trade is subject to iceberg costs. Country i must purchase $d_{ij} \geq 1$ units of an intermediate variety from country j in order for one unit to arrive; $d_{ij} - 1$ units melt away in transit. As a normalization, we assume that $d_{ii} = 1$ for all i.

2.3 Preferences

The representative household's lifetime utility is given by

$$\sum_{t=1}^{\infty} \beta^{t-1} \frac{(C_{it}/L_i)^{1-1/\sigma}}{1-1/\sigma},$$

where C_{it}/L_i denotes consumption per worker in country i at time t, $\beta \in (0,1)$ denotes the period discount factor, and σ denotes the intertemporal elasticity of substitution.

2.4 Equilibrium

At each point in time, we take world GDP as the numéraire: $\sum_i r_{it}K_{it} + w_{it}L_i = 1$ for all t. That is, all prices are expressed in units of current world GDP.

A competitive equilibrium satisfies the following conditions: (i) Taking prices as given, the representative household in each country maximizes its lifetime utility subject to its budget constraint and technology for capital accumulation; (ii) taking prices as given, firms maximize profits subject to the available technologies; (iii) intermediate varieties are purchased from their lowest-cost provider subject to the trade costs; and (iv) all markets clear. We describe each equilibrium condition in more detail in Appendix A.

In addition to the above equilibrium conditions, a steady state is characterized by a balanced current account and time-invariant consumption, output, capital stock, and the NFA position. In the steady state, net foreign income exactly offsets the trade imbalance.

2.5 Welfare gains

We compute transition paths for several counterfactuals starting from an initial steady state to a final steady state. We measure the resulting changes in welfare using consumption-equivalent units as in Lucas (1987). Let $c_i \equiv C_i/L_i$ denote consumption per worker in country i. The *dynamic gain* in country i is measured by λ_i^{dyn}, which solves

$$\sum_{t=1}^{\infty} \beta^{t-1} \frac{\left(\left(1+\frac{\lambda_i^{dyn}}{100}\right) c_i^{\star}\right)^{1-1/\sigma}}{1-1/\sigma} = \sum_{t=1}^{\infty} \beta^{t-1} \frac{\left(\tilde{c}_{it}\right)^{1-1/\sigma}}{1-1/\sigma}, \tag{1}$$

where $c_i^{\star}$ is the initial steady-state consumption and $\tilde{c}_{it}$ is the time-t counterfactual consumption.

The transition path for consumption depends on the path for income. We denote real income per worker as $y_{it} \equiv \frac{r_{it}K_{it}+w_{it}L_i}{P_{cit}L_i}$ and the capital-labor ratio as $k_{it} \equiv \frac{K_{it}}{L_i}$. In Appendix B we show that

$$y_{it} \propto \underbrace{\left(\frac{A_{ci}}{B_{ci}}\right) \left(\frac{\left(\frac{T_{mi}}{\pi_{iit}}\right)^{\frac{1}{\theta}}}{B_{mi}}\right)^{\frac{1-\nu_{ci}}{\nu_{mi}}}}_{\text{TFP}} \left(k_{it}\right)^{\alpha}, \tag{2}$$

where $B_{ci} = (\alpha\nu_{ci})^{-\alpha\nu_{ci}} \left((1-\alpha)\nu_{ci}\right)^{-(1-\alpha)\nu_{ci}} (1-\nu_{ci})^{-(1-\nu_{ci})}$ and B_{mi} is defined analogously by replacing ν_{ci} with ν_{mi}. In equation (2), the capital-labor ratio is endogenous and is also a function of the home trade share.

Channels for the gains from trade Trade liberalization affects the dynamic gain in our model through two channels.

1. Trade liberalization results in an immediate and permanent drop in the home trade share and, hence, higher TFP on impact. The higher TFP increases GDP and affects the consumption path. The tradables intensity of consumption goods governs the responsiveness of TFP to the change in the home trade share.

2. Trade liberalization also increases the rate of capital accumulation due to the increase in TFP and decrease in the price of intermediates. The responsiveness of capital depends on the tradables intensity of investment. The increase in TFP yields a higher marginal product of capital (MPK), which affects capital accumulation and, hence, income and consumption. The higher the intensity of tradables in investment goods production,

the larger the response of investment to the decline in the price of intermediates. Thus, the transition paths of income and consumption are affected.

Dynamics The dynamics are governed by two intertemporal Euler equations associated with the one-period bond and capital:

$$\frac{c_{it+1}}{c_{it}} = \beta^{\sigma} \left(\frac{1 + q_{t+1}}{P_{cit+1}/P_{cit}} \right)^{\sigma} \tag{3}$$

$$\frac{c_{it+1}}{c_{it}} = \beta^{\sigma} \left(\frac{\frac{r_{it+1}}{P_{ixt+1}} - \Phi_2(k_{it+2}, k_{it+1})}{\Phi_1(k_{it+1}, k_{it})} \right)^{\sigma} \left(\frac{P_{xit+1}/P_{cit+1}}{P_{xit}/P_{cit}} \right)^{\sigma}, \tag{4}$$

where $\Phi_1(\cdot, \cdot)$ and $\Phi_2(\cdot, \cdot)$ denote the first derivatives of the adjustment-cost function with respect to the first and second arguments, respectively:

$$\Phi_1(k', k) = \delta^{\frac{\lambda-1}{\lambda}} \left(\frac{1}{\lambda} \right) \left(\frac{k'}{k} - (1 - \delta) \right)^{\frac{1-\lambda}{\lambda}}$$

$$\Phi_2(k', k) = \delta^{\frac{\lambda-1}{\lambda}} \left(\frac{1}{\lambda} \right) \left(\frac{k'}{k} - (1 - \delta) \right)^{\frac{1-\lambda}{\lambda}} \left((\lambda - 1)\frac{k'}{k} - \lambda(1 - \delta) \right),$$

where the prime notation denotes the next period's value.

The dynamics are pinned down by the solution to a system of $2 \times I$ simultaneous, second-order, nonlinear difference equations. The evolution of capital in country i depends on the capital stocks in all other countries due to trade. The Euler equations reveal that a change in trade costs for any country at any point in time affects the dynamic path of all countries.

3 Calibration

We calibrate the parameters of our model to match several observations in 2014. We assume that the world is in steady state in 2014. Our data cover 44 countries (more precisely, 43 countries plus a rest-of-the-world (ROW) aggregate). Table C.1 in Appendix C provides a list of the countries. The primary data sources include version 9.0 of the Penn World Table (PWT) (Feenstra, Inklaar, and Timmer, 2015) and the WIOD (Timmer, Dietzenbacher, Los, Stehrer, and de Vries, 2015; Timmer, Los, Stehrer, and de Vries, 2016). More details about the data are provided in Appendix C.

Initial steady state With endogenous trade imbalances, the transition path and the steady state are determined jointly. To compute the initial steady state, we use two properties to specify the NFA positions, $\mathcal{A}_{i1}$, in every country: (i) The world interest rate is $q = 1/\beta - 1$, and (ii) the current account is balanced. These two properties imply that $\mathcal{A}_{i1}$ satisfies $NX_i = -q\mathcal{A}_i$; i.e., the net exports, NX_i, are offset by net foreign income. We choose net foreign income so that the net exports are those observed in 2014. The initial steady state is then characterized by a set of nonlinear equations; see Table A.2 in Appendix A.

3.1 Common parameters

The values for the common parameters are reported in Table 1. We use recent estimates of the trade elasticity by Simonovska and Waugh (2014) and set $\theta = 4$. We set $\eta = 2$, which satisfies the condition $1 + \frac{1}{\theta}(1 - \eta) > 0$. This value plays no quantitative role in our results.

In line with the literature, we set the share of capital in value added to $\alpha = 0.33$ (Gollin, 2002), the discount factor to $\beta = 0.96$ so that the steady-state real interest rate is about 4 percent, and the intertemporal elasticity of substitution to $\sigma = 0.5$.

The rate of depreciation for capital is set to $\delta = 0.06$. The elasticity of capital accumulation with respect to investment, λ, is set to 0.76.[5]

Table 1: Common parameters

Trade elasticity	θ	4
Elasticity of substitution between intermediate varieties	η	2
Capital's share in value added	α	0.33
Discount factor	β	0.96
Intertemporal elasticity of substitution	σ	0.5
Depreciation rate for capital	δ	0.06
Adjustment cost elasticity	λ	0.76

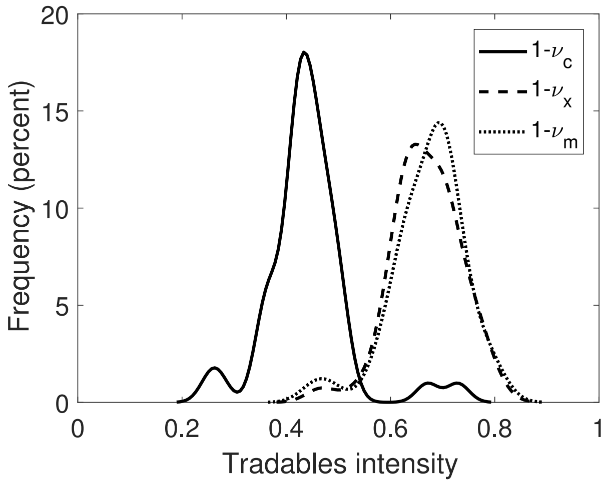
3.2 Country-specific parameters

As noted earlier, with $q = 1/\beta - 1$, we choose $\mathcal{A}_{i1}$ to be consistent with the observed net exports in each country in 2014; the current account balance is zero.

[5] Eaton, Kortum, Neiman, and Romalis (2016) calibrate this value to be 0.5 for investment in structures and 0.55 for investment in equipment in a model that uses quarterly data. First, we compute the average between the two, as we have only one investment good. Second, since our model period is a year and the quarterly values likely overestimate the annual adjustment cost, we take the midpoint between the average of their estimates and 1, where $\lambda = 1$ corresponds to no adjustment costs.

We calibrate ν_{mi}, ν_{xi}, and ν_{ci} using data from the WIOD. We set ν_{mi} as the ratio of value added to gross output for non-durable goods production in each country, which covers two-digit categories 01-28 in revision 3 of the International Standard Industrial Classification of All Economic Activities (ISIC). We set ν_{xi} as the ratio of value added to gross output for durable goods (ISIC categories 29-35) and construction (ISIC category 45). Finally, we compute the remainder of value added and gross output in each country for those sectors that are not accounted for by sectors m and x to obtain values for ν_{ci} in each country. The cross-country heterogeneity in the intensities in each sector is illustrated in Figure 1. The cross-country averages for $1-\nu_m, 1-\nu_x$, and $1-\nu_c$ are 0.67, 0.67, and 0.44, respectively.

Figure 1: Tradables intensity in each sector



Notes: The letters c, x, and m denote the consumption, investment, and intermediate sectors, respectively.

We set the workforce, L_i, equal to the employment in country i in 2014, documented in PWT. The remaining parameters A_{ci}, T_{mi}, A_{xi}, and d_{ij}, for $(i,j) = 1, \ldots, I$, are not directly observable. We infer these by linking steady-state relationships of the model to observables.

The equilibrium structure relates the trade costs between any two countries to the ratio of intermediate goods prices in the two countries and the trade shares:

$$\frac{\pi_{ij}}{\pi_{jj}} = \left(\frac{P_{mj}}{P_{mi}}\right)^{-\theta} d_{ij}^{-\theta}. \tag{5}$$

For observations where $\pi_{ij} = 0$, we set $d_{ij} = 10^8$. We also set $d_{ij} = 1$ if the inferred value of trade cost is less than 1.[6] Lastly, we use three structural relationships to pin down the productivity parameters A_{ci}, T_{mi}, and A_{xi}:

$$\frac{P_{ci}}{P_{mi}} \propto \left(\frac{B_{ci}}{A_{ci}}\right)\left(\frac{\left(\frac{T_{mi}}{\pi_{ii}}\right)^{\frac{1}{\theta}}}{B_{mi}}\right)^{\frac{\nu_{ci}}{\nu_{mi}}} \tag{6}$$

$$\frac{P_{xi}}{P_{mi}} \propto \left(\frac{B_{xi}}{A_{xi}}\right)\left(\frac{\left(\frac{T_{mi}}{\pi_{ii}}\right)^{\frac{1}{\theta}}}{B_{mi}}\right)^{\frac{\nu_{xi}}{\nu_{mi}}} \tag{7}$$

$$y_i \propto \left(\frac{A_{ci}}{B_{ci}}\right)\left(\frac{\left(\frac{T_{mi}}{\pi_{ii}}\right)^{\frac{1}{\theta}}}{B_{mi}}\right)^{\frac{1-\nu_{ci}}{\nu_{mi}}} (k_i)^{\alpha}. \tag{8}$$

The terms B_{ci}, B_{mi}, and B_{xi} are country-specific constants that depend on $\alpha, \nu_{ci}, \nu_{mi}$, and ν_{xi}. Equations (6)–(8) are derived in Appendix B. The three equations relate observables—the price of consumption relative to intermediates, the price of investment relative to intermediates, income per worker, capital stocks, and home trade shares—to the unknown productivity parameters. We normalize $A_{ci} = T_{mi} = A_{xi} = 1$ for the United States. For each country, the three equations (6)–(8) have three unknowns: A_{ci}, T_{mi}, and A_{xi}. Information on the empirical counterparts to $P_{ci}, P_{mi}, P_{xi}, y_i, k_i$, and π_{ii} is in Appendix C.

These equations are intuitive. The expression for income per worker provides a measure of aggregate productivity across all sectors: Higher income per worker is associated with higher productivity levels, on average. The expressions for relative prices boil down to two components. The first term reflects something akin to the Balassa-Samuelson effect: All else equal, a higher price of capital relative to intermediates suggests low productivity in the capital goods sector relative to the intermediate goods sector. In our setup, the measured productivity for intermediates is endogenous and depends on the degree of specialization as captured by the home trade share. The second term reflects the relative intensity of intermediate inputs. If measured productivity is high for the intermediates, then the price of intermediates is relatively low and the sector that uses intermediates more intensively will have a lower relative price. In our calibration, as Figure 1 illustrates, the intermediates are more intensively used in the capital goods sector; that is, $1 - \nu_{xi} > 1 - \nu_{ci}$.

[6] For the two-country version in Appendix F, all of the countries in ROW would have *no cost* to trade with each other, by assumption.

3.3 Model fit

Our model has 2021 unobservable country-specific parameters: $I \times (I-1) = 1892$ bilateral trade costs plus $(I-1) = 43$ consumption-good productivity terms plus $(I-1) = 43$ investment-good productivity terms plus $(I-1) = 43$ intermediate-goods productivity terms.

Calibration of the country-specific parameters uses a total of 2107 data points. The trade costs use $I \times (I-1) = 1892$ data points for the bilateral trade shares and $(I-1) = 43$ for the ratio of absolute prices of intermediates. The productivity parameters use $(I-1) = 43$ data points for the price of consumption relative to intermediates plus $(I-1) = 43$ data points for the price of investment relative to intermediates plus $(I-1) = 43$ data points for income per worker plus $(I-1) = 43$ data points for capital stocks.

The model matches the targeted data well. The correlation between the model and the data is 0.97 for bilateral trade shares. The correlation is 0.62 for the absolute price of intermediates, 0.94 for income per worker, 0.99 for the price of consumption relative to intermediates, and 0.99 for the price of investment relative to intermediates. Our model also matches the targeted ratio of net exports to GDP; the correlation is 0.98.

We use prices of consumption and investment, relative to intermediates, in our calibration. The correlation between the model and the data is 0.98 for the absolute price of consumption and 0.97 for the absolute price of investment. The correlation for the price of investment relative to consumption is 1.00.

Untargeted moments The correlation between the model and the data on capital-labor ratios is 0.76. The correlation is low because, in the model, we are imposing a steady-state relation between investment and capital: $K_i^\star = \frac{X_i^\star}{\delta}$. In the data, this relationship need not hold. If we use the observed investment and measure the capital-labor ratio via the steady-state relationship, the correlation between the model and the data is 0.91.

The cross-country average nominal investment rate, $\frac{P_x X}{wL + rK}$, is 17.2 percent in the model and 22.5 percent in the data. In both the model and the data, the nominal investment rate is uncorrelated with income per worker. Part of the reason for the lower nominal investment rate in the model relative to the data is that the rate in the model depends only on the fundamental parameters: the adjustment cost λ, capital's share α, the discount factor β, and the depreciation rate δ. Removing the adjustment cost (set $\lambda = 1$) increases the mean nominal investment rate from 17.2 percent to 19.5 percent. In addition to removing the adjustment cost, if we increase the depreciation rate from 0.06 to 0.08, then the nominal investment rate increases to 21.7 percent.

4 Counterfactuals

In this section, we implement a counterfactual trade liberalization via an unanticipated, uniform, and permanent reduction in trade costs. The world begins in the calibrated steady state. At the beginning of period $t = 1$, trade costs fall uniformly by 20 percent in all countries. This amounts to reducing $d_{ij} - 1$ by 20 percent for each country pair i, j. All other parameters are fixed at their calibrated values. Note that reductions of trade costs $(d_{ij} - 1)$ require knowing the initial value of d_{ij}.[7]

4.1 Computing the counterfactual transition path and steady state

The main challenge in solving dynamic multicountry trade models is the curse of dimensionality. Computing the dynamic paths requires solving intertemporal Euler equations, and each one of our Euler equations is a second-order, nonlinear difference equation. In closed economies or two-country models, recursive methods such as value function iteration or policy function iteration can be employed efficiently by discretizing the state space for capital stocks in each country. However, in our world with 44 countries and two state variables, n discrete values for each state variable would imply $n^{44} \times n^{44}$ grid points in the state space. An alternative is to use shooting algorithms that involve iterating on guesses for the entire path of state variables in every country. Each iteration, however, involves computing gradients to update the entire path. With T periods, 44 countries, and two state variables, the updates require $T \times 44 \times 2$ gradients, and each gradient requires solving the entire model.

Our method iterates on prices and investment rates. We use excess demands to determine the size and direction of the change in prices and investment rates in each iteration. We bypass the costly computation of gradients and compute the entire transition path in 31 minutes on a standard 3.2 GHz Intel i5 iMac.

To compute the counterfactual transition path and steady state, we first reduce the infinite horizon problem to a finite horizon model with T periods. We make T sufficiently large to ensure convergence to a new steady state; $T = 150$ proved sufficient in our computations.

We start with a guess: The terminal NFA position $\mathcal{A}_{iT+1} = 0$ for all i. We then guess the entire sequences of nominal investment rates, $\rho_{it} = \frac{P_{xit}X_{it}}{w_{it}L_{it}+r_{it}K_{it}}$, and wages for every

[7]Denote the counterfactual trade cost by $d_{ij}^{cf} - 1$. Then, reducing the trade costs uniformly by 20 percent implies $(d_{ij}^{cf} - 1) = 0.8(d_{ij} - 1)$. The change $\hat{d}_{ij} \equiv \frac{d_{ij}^{cf}}{d_{ij}} = \frac{0.2}{d_{ij}} + 0.8$ clearly depends on the initial d_{ij}. The hat-algebra approach does not need the initial d_{ij} and would set $\hat{d}_{ij} = 0.8$. If we follow that approach, we would violate the restriction $d_{ij}^{cf} \geq 1$ for several bilateral trade costs.

country, as well as one sequence of world interest rates. Taking the nominal investment rate as given, we iterate over wages and the world interest rate using excess demand equations. The wages and the world interest rate help us recover all other prices and trade shares from first-order conditions and a subset of market-clearing conditions. We use deviations from (i) the balance-of-payments identity in each country—net purchases of bonds equals net exports plus net foreign income—and (ii) the trade balance at the world level—global imports equals global exports—to update the sequences of wages in every country and the world interest rate simultaneously. We repeat the process until we find sequences that satisfy the balance of payments and world trade balance. With these sequences, we check whether the Euler equation for investment in capital is satisfied. We use deviations from the Euler equation to update the nominal investment rate in every country at every point in time simultaneously. Using the transition path of the NFA position, we update the terminal $\mathcal{A}_{iT+1}$ by setting it to $\mathcal{A}_{it}$, where t is some period close to but less than T. We continue this procedure until we reach a fixed point in the sequence of nominal investment rates and the steady-state NFA position. Appendix D describes our solution method in more detail. Our method is also valid for the environment with multiple sectors and a complete IO structure (Appendix G).

The presence of both capital and bonds introduces a challenge in computing transitional dynamics. To see why, consider a model with one-period bonds but no capital accumulation, as in Reyes-Heroles (2016). In such a model, the counterfactual steady state is reached immediately after the *change* in the exogenous "shock" is zero. For our trade liberalization, the world would reach the counterfactual steady state immediately. In a sense, there are no transitional dynamics and one can thus determine the time taken to reach the new steady state just by assuming when the change in the shock is zero; the mechanisms in the model have nothing to say about when the new steady state is reached. In our model with capital, the time taken to reach the new steady state is endogenous. That is, even though the change in the shock is zero after the liberalization, the world reaches the new steady state several periods later. How long it takes to reach the new steady state depends on model elements: the time to build, adjustment costs, consumption smoothing, etc.

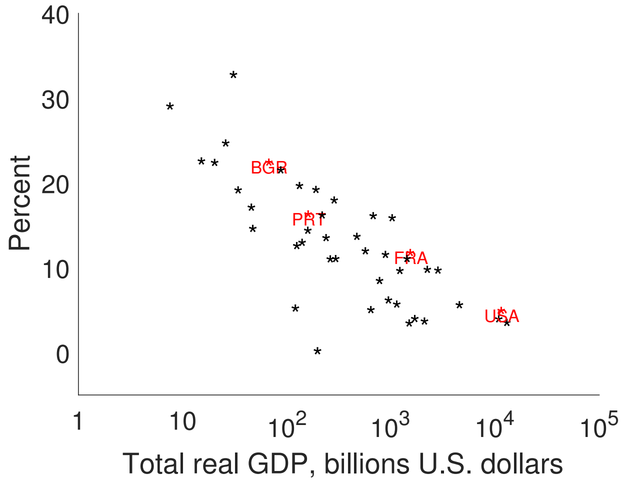
Eaton, Kortum, Neiman, and Romalis (2016) use the "hat algebra" approach to solve for *changes* in endogenous variables; Zylkin (2016) uses a similar approach to study the dynamic effects of China's integration into the world economy. The computation of the counterfactual in these papers can proceed without knowing the initial trade costs. For counterfactual exercises such as ours, one needs to know the initial trade costs (see the example in footnote

6). Conditional on knowing them, the hat algebra approach is essentially equivalent to ours.[8]

4.2 Dynamic gains from trade

As noted earlier, the dynamic gain for country i, λ_i^{dyn}, is given by equation (1). Figure 2 illustrates the dynamic gains from a 20 percent reduction in trade costs for the 44 countries in our sample. Throughout the remainder of the paper, we not only use scatter plots, as in Figure 2, but we also use four countries to highlight our results: Bulgaria, Portugal, France, and the United States. These four countries provide a representative sample of gains and of size, measured by total real GDP.

Figure 2: Distribution of gains from trade



Notes: Horizontal axis—Total real GDP data for 2014. Vertical axis—Dynamic gains (percent) following an unanticipated, uniform, and permanent 20 percent trade liberalization. The gain for Norway is negative, which is due to its large negative NFA position in the initial steady state.

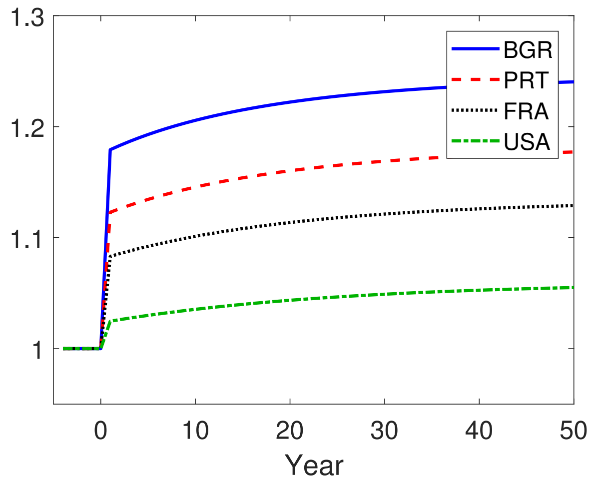
The gains from trade vary substantially across countries: The gain for the United States is 4.4 percent, while the gain for Bulgaria is 22 percent. The gains are smaller for large countries, similar to the findings in Waugh and Ravikumar (2016) and Waugh (2010). Since the size of liberalization is the same for all countries, the implied elasticities—the percent increase in welfare due to the percent decrease in trade cost—are also different across countries. The elasticity is roughly 0.22 for the United States and 1.09 for Bulgaria. (In Appendix

[8]Caliendo, Dvorkin, and Parro (2018) use excess demand iteration and hat algebra in a model without capital and with *intratemporal* transfers to study how higher TFP in China affects U.S. labor markets.

G, we find that the welfare gains in a model with more sectors and a complete IO structure are highly correlated with the gains above.)

The consumption paths that generate the gains are illustrated in Figure 3 for the four countries. Bulgaria, for instance, not only experiences a larger increase in consumption immediately after the trade liberalization, but also ends up with a larger increase in consumption across steady states, relative to the United States. The percent change in consumption across steady states—steady-state gains—exceeds the dynamic gains in all countries. The dynamic gains are, on average, about 80 percent of the steady-state gains, meaning that about 20 percent of the steady-state increase in consumption is *lost* along the transition. The ratio of dynamic to steady-state gains ranges from 63 percent to 92 percent.

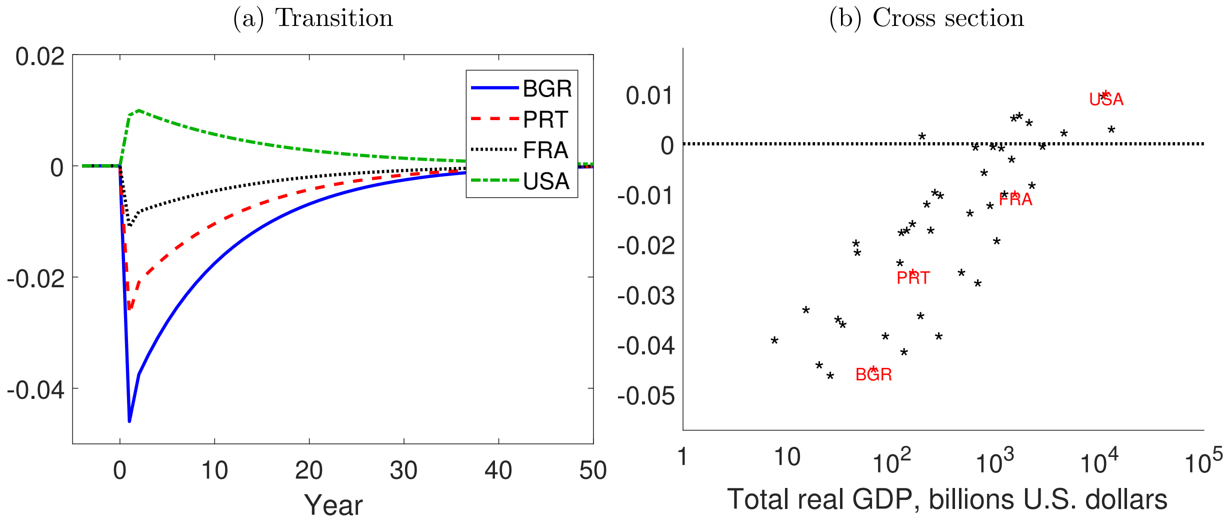
Figure 3: Transition path for consumption



Notes: Transitions following an unanticipated, uniform, and permanent 20 percent trade liberalization. The initial steady state is normalized to 1. The liberalization occurs in period 1.

The manner in which consumption is financed differs across countries. Figure 4 illustrates the current accounts. Recall that all countries start from an initial steady state with a zero current account balance. The United States accumulates a current account surplus immediately after the liberalization, whereas Bulgaria accumulates a current account deficit. The current account balance is positively correlated with country size. Financial resources flow from large countries to small countries and boost consumption in small countries. The current account dynamics imply that larger countries tend to backload consumption, whereas smaller countries tend to frontload consumption. As a result, the ratio of dynamic to steady-state gains decreases with country size: 0.89 for Bulgaria and 0.74 for the United States.

Figure 4: Ratio of current account to GDP



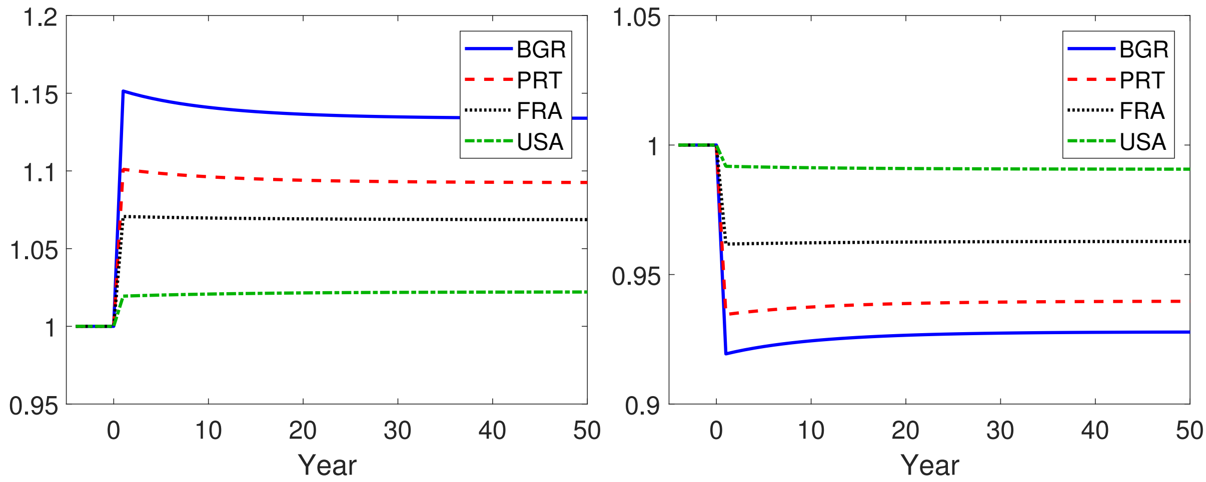
Notes: Results following an unanticipated, uniform, and permanent 20 percent trade liberalization. The current account balance is zero in the initial steady state. Panel (a): The liberalization occurs in period 1. Panel (b): The ratio of the current account to GDP, computed in period 1. Horizontal axis—Total real GDP data for 2014.

TFP and capital accumulation Trade liberalization reduces each country's home trade share immediately, increasing TFP and reducing the relative price of investment (Figure 5). The immediate increase in TFP increases each country's output; capital does not change on impact. Higher output makes more consumption and investment feasible. The dynamics of consumption and investment are governed by the relative price of investment and the return to capital, as revealed by Euler equation (4). Investment increases by more than consumption because (i) the relative price of investment decreases and (ii) higher TFP causes MPK to increase. As capital accumulates, output continues to increase. The increase in output on impact is entirely due to TFP, whereas the increase in output after the initial period is driven entirely by capital accumulation (Figure 6).

With a frictionless bond market, MPKs are equalized across countries and resources flow to countries that experience a larger increase in TFP. These countries run a current account deficit in the short run and use it to finance increases in consumption and investment that exceed increases in output (e.g., Bulgaria, Portugal, and France). In the new steady state the current account is balanced, but countries that accumulate debt along the transition have to eventually run trade surpluses to service the debt. In general, small countries run current account deficits and large countries run current account surpluses in the short run.

Figure 5: Transition path for TFP and price of investment relative to consumption

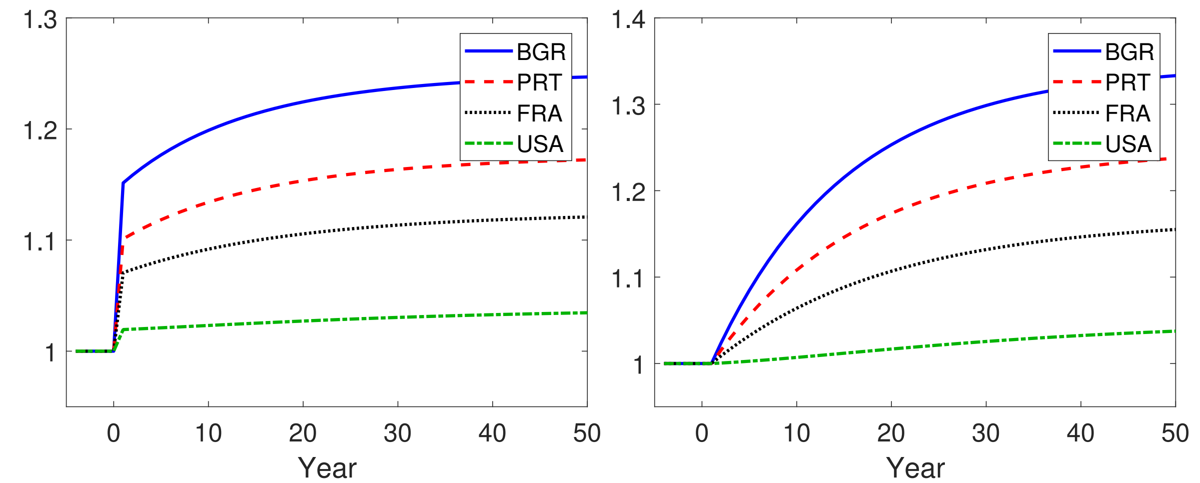
(a) TFP (b) Relative price of investment



Notes: Transitions following an unanticipated, uniform, and permanent 20 percent trade liberalization. The initial steady state is normalized to 1. The liberalization occurs in period 1.

Figure 6: Transition path for income per worker and capital

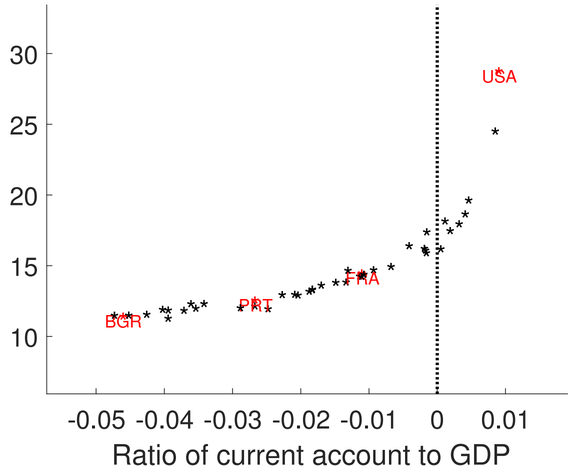
(a) Income per worker (b) Capital-labor ratio



Notes: Transitions following an unanticipated, uniform, and permanent 20 percent trade liberalization. The initial steady state is normalized to 1. The liberalization occurs in period 1.

Half life The behavior of trade imbalances also reveals a pattern in the rates of capital accumulation. Figure 7 illustrates that the half-life for capital accumulation—the number of years it takes for the capital stock to reach the midpoint between the initial and counterfactual steady-state values—varies with trade deficits.

Figure 7: Half-life for capital



Notes: Half-life for an unanticipated, uniform, and permanent 20 percent trade liberalization. The liberalization occurs in period 1. Horizontal axis—Ratio of current account to GDP, computed in period 1. Vertical axis—Half-life for capital, computed as the number of years it takes for the capital stock to reach the midpoint between the initial and counterfactual steady-state values.

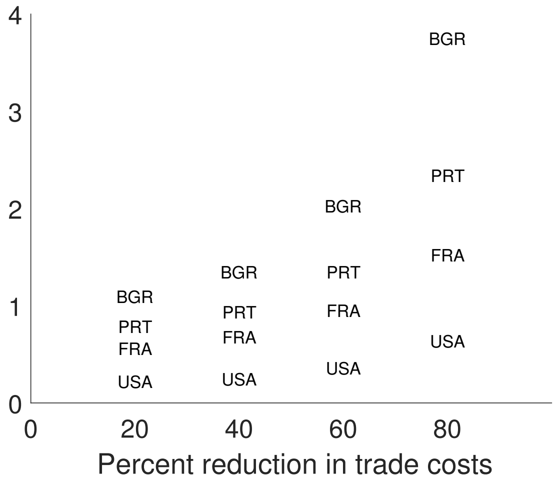
Countries with larger short-run trade deficits have lower half-lives; i.e., they accumulate capital faster. Bulgaria closes 50 percent of the gap between its two steady-state values of capital in roughly 11 years, whereas it takes 28 years for the United States.

Nonlinear gains Welfare gains from trade are nonlinear in the size of the trade liberalization. To illustrate these nonlinearities, we examine the elasticity of gains, computed as the absolute value of the percent change in welfare divided by the percent change in export-weighted trade costs. The export-weighted trade costs are computed as

$$\bar{d}_i = \frac{\sum_{\substack{j=1 \\ j\neq i}}^{I} TRD_{ji} d_{ji}}{\sum_{\substack{j=1 \\ j\neq i}}^{I} TRD_{ji}}. \tag{9}$$

Figure 8 shows the elasticity of gains for Bulgaria, Portugal, France, and the United States, for 20, 40, 60, and 80 percent trade cost reductions. The gains increase exponentially with the size of liberalization, and the increase is larger for small countries. The elasticity for Bulgaria ranges from 1.09 for a 20 percent trade liberalization to 3.75 for an 80 percent liberalization. The corresponding range for the United States is 0.22 to 0.64.

Figure 8: Elasticity of dynamic gains



Notes: The elasticity is computed as the absolute value of the percent change in welfare divided by the percent change in trade cost.

4.3 Other counterfactuals

Non-uniform trade liberalization Our previous counterfactuals considered uniform reductions in trade costs across countries. In practice these trade costs include policy-induced impediments to trade as well as barriers not directly influenced by policy, such as geography. Most trade liberalizations involve reducing the policy-induced impediment to trade. Since the relative importance of this component is heterogeneous across countries, these trade liberalizations are non-uniform. We now consider a counterfactual trade liberalization in which we remove the policy-induced impediments to trade.

In order to isolate the policy component, we project the calibrated bilateral trade costs onto an exporter fixed effect and symmetric gravity variables including geographic distance, a common border, a common language, and a common currency (Centre d'Etudes Prospectives et d'Informations Internationales (CEPII)).

We estimate the following equation:

$$\log(d_{ij}) = \sum_{k=1}^{6} dist_{ij}^{k} + brdr_{ij} + lang_{ij} + curr_{ij} + e_j + \varepsilon_{ij}, \tag{10}$$

where $dist_{ij}^{k}$ is the contribution to trade costs of the distance between country j and i falling into the k^{th} interval (in miles), defined as [0, 350], [350, 750], [750, 1500], [1500, 3000], [3000, 6000], [6000, maximum]. The term e_j is an exporter fixed effect, as in Waugh (2010).

Our assumption is that the impediments to trade that stem from the gravity variables cannot be altered by trade policy. The remainder of the trade costs—the exporter fixed effect and the residual—are asymmetric and could be affected by policy changes. We consider a policy that removes all asymmetries in trade costs. We achieve this by (i) setting the exporter fixed effect in each country equal to the minimum exporter fixed effect across countries (Germany in our sample) and (ii) setting the residual for each country pair to the minimum value between the countries. For example, $\tilde{\varepsilon}_{ij} = \min(\varepsilon_{ij}, \varepsilon_{ji})$. Feature (ii) implies that after controlling for geography, there should be no difference between the cost of shipping from Cyprus to Germany and that of shipping from Germany to Cyprus.

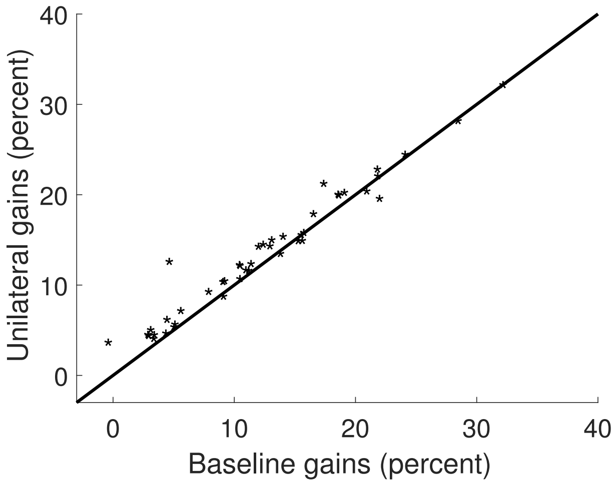
In our counterfactual, the export-weighted trade costs fall by 73 percent in Bulgaria and in Portugal, 50 percent in France, and 31 percent in the United States. The elasticity of the gains associated with these reductions is 7.4 for Bulgaria, 3.5 for Portugal, 1.8 for France, and 0.7 for the United States. These elasticities imply that the scope for welfare gains through policy reform is greater for countries like Bulgaria than for countries like the United States.

Unilateral trade liberalization In the counterfactuals so far, the trade liberalization has been across all of the 44 countries simultaneously. Here we reduce a specific country's trade costs—both imports and exports—by 20 percent.

When the United States reduces its trade costs unilaterally, its gain is 4.2 percent. Similarly, for Bulgaria the gain is 21.6 percent, for Portugal it is 15.3 percent, and for France it is 11.1 percent. Figure 9 illustrates the unilateral gains for our entire sample of countries. The magnitude of the gains is close to the baseline dynamic gains (see Figure 2). The correlation between the gains in the two experiments is 0.98.

For most countries, the unilateral gain is more than the baseline dynamic gain computed in Section 4.2. This is because the change in the world interest rate after the liberalization is negligible in the unilateral case, while it increases by 21 basis points in our counterfactual in Section 4.2. The increase in the world interest rate lowers the baseline dynamic gains of countries with a negative initial NFA position, but increases the gains for countries with a positive initial NFA position. The same countries are not affected by the interest rate in the unilateral case. As a result, the dispersion of gains is smaller in the unilateral case (standard deviation of 6.9 percent versus 7.4 percent in the baseline).

Figure 9: Dynamic gains from trade



Notes: Horizontal axis—Baseline dynamic gains. Vertical axis—Dynamic gains following an unanticipated, *unilateral*, and permanent 20 percent trade liberalization.

5 Capital accumulation and intensities of tradables

Different from static models, our framework delivers gains due to capital accumulation. In addition, the intensities of tradables play a quantitatively important role in the dynamics of TFP and capital accumulation. In this section we analyze the importance of each of these.

5.1 Role of capital accumulation

To illustrate the role of capital accumulation in delivering the gains from trade, we use the counterfactual *income* path from Figure 6a and construct a gain based on the immediate change in income per worker and compare the gain to the dynamic gain in Section 4.2. We exploit the fact that after an unanticipated trade liberalization in our model, capital does not change on impact and the changes in TFP are immediate (see Figure 5). Thus, the change in income on impact captures the immediate, or "static," gain. Our immediate gain calculation is in the same spirit as the static gain computation in the literature (e.g., ACR) since the gain is entirely due to changes in TFP resulting from changes in the home trade share. The dynamic gain, on the other hand, includes capital accumulation, by construction.

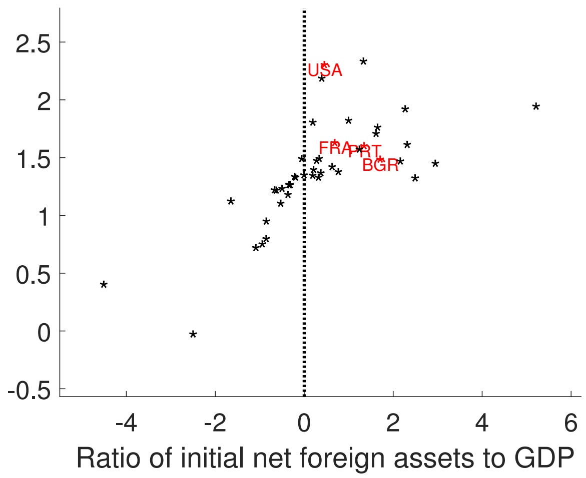
Using the income path in Figure 6a, we compute the immediate gain as

$$1 + \frac{\lambda_i^{immediate}}{100} = \frac{y_{i1}}{y_i^\star}, \tag{11}$$

where y_{i1} is the income per worker in country i in period 1 in Figure 6a and $y_i^\star$ is the income per worker in the initial steady state in country i. Note that, conditional on the income path, the immediate gain does not depend on the preference parameters.

The dynamic gains are the same as in Section 4.2. Figure 10 illustrates the ratio of dynamic gain to immediate gain for each country. On average, the dynamic gain is 35 percent more than the immediate gain. Since capital does not change immediately after liberalization, the additional 35 percent in the dynamic gain is due to capital accumulation. The ratio in Figure 10 ranges from -0.07 to almost 2.29. The negative ratio is for Norway, whose dynamic gain is negative, as noted earlier in Figure 2. The ratio is positively correlated with the initial NFA position: Countries with a negative initial NFA position have a lower ratio compared to countries with a positive position since the world interest rate increases in our model immediately after liberalization.

Figure 10: Ratio of dynamic to immediate gains in the baseline model



Notes: Horizontal axis—NFA position in the initial steady state. Vertical axis—Ratio of dynamic gains to immediate gains using the counterfactual income path in the baseline model.

In Appendix E, we compute the static gains in an alternative manner by taking the capital stock as an exogenous endowment as in Waugh (2010). This requires re-calibrating the model. Nonetheless, we find that the gains in that model are practically identical to the immediate gains computed above; see equations (E.1) and (E.2) and Figure (E.2).

5.2 Role of the intensities of tradables

Recall that in our model, $1-\nu_{ci}$ denotes the tradables intensity for consumption goods and $1-\nu_{xi}$ denotes that for investment goods in country i. These are heterogeneous across countries. In this section, we examine the quantitative role of each intensity.

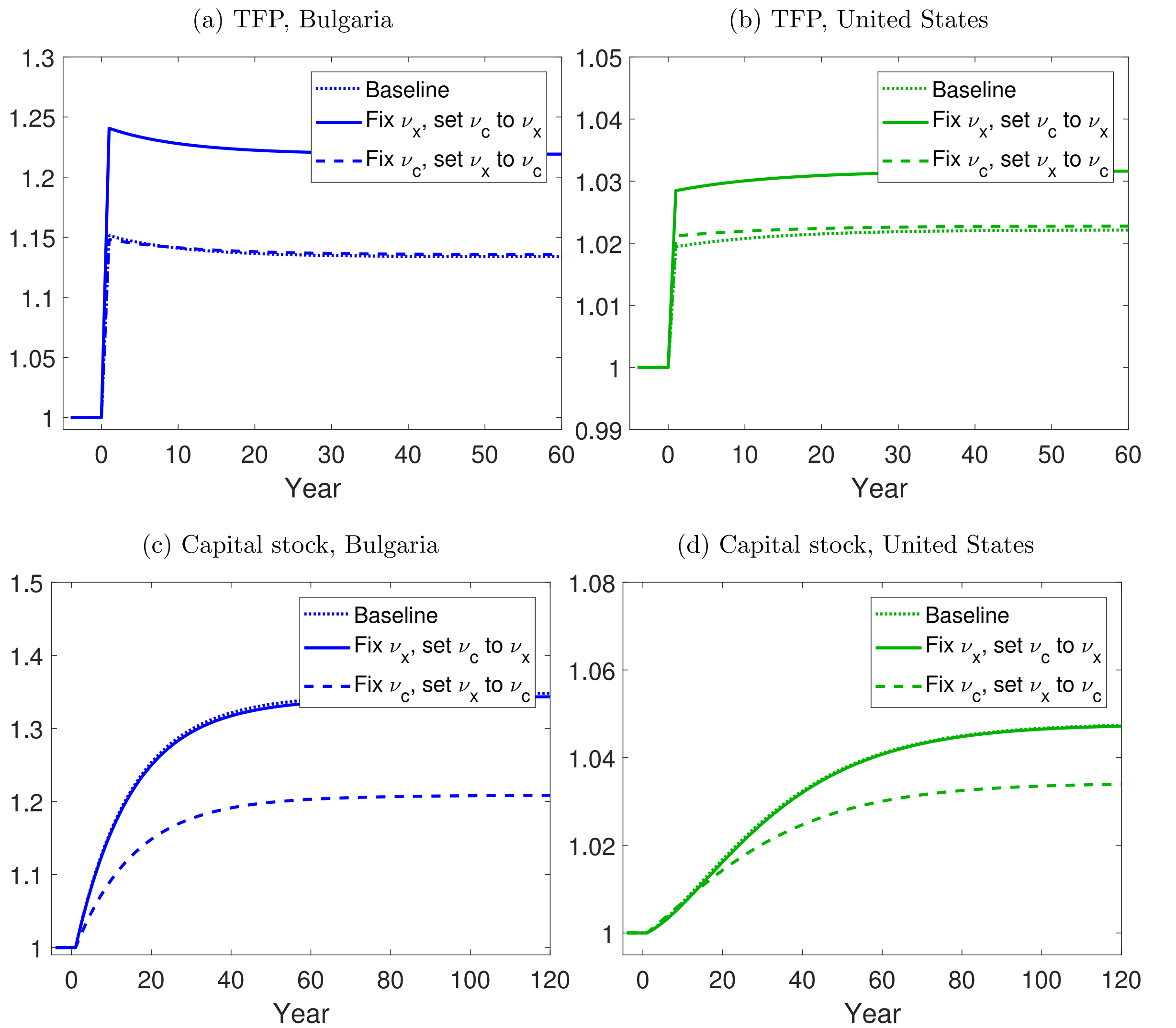
Mutreja, Ravikumar, and Sposi (2018) already demonstrated that the *difference* between the tradables intensities in consumption and investment goods, $\nu_{ci}-\nu_{xi}$, characterizes the response of the price of investment relative to consumption and, hence, the investment rate and capital accumulation. In their exercise, there is no cross-country heterogeneity in the difference between the two intensities; furthermore, ν_c is the same across countries and so is ν_x. Here, we examine the implications of cross-country heterogeneity in ν_c and ν_x.

We consider two specifications: (i) Keep ν_{ci} fixed to its calibrated value and increase ν_{xi} to equal ν_{ci}, thereby making investment goods less tradables intensive relative to the baseline, and (ii) keep ν_{xi} fixed to its calibrated value and decrease ν_{ci} to equal ν_{xi}, thereby making consumption goods more tradables intensive. In both specifications we consider the 20 percent trade liberalization and examine the responses of TFP and capital accumulation. Note that both (i) and (ii) allow for ν_{xi} and ν_{ci} to vary across countries, but they ensure that $\nu_{xi}-\nu_{ci}=0$ for all i. Thus, the relative price does not respond to the trade liberalization and, hence, we don't re-examine the channel for capital accumulation explored in Mutreja, Ravikumar, and Sposi (2018).

Figure 11 illustrates the results for Bulgaria and the United States. In specification (i), when we fix ν_{ci} to its calibrated value, TFP follows the same path as in the baseline model, even though ν_{xi} differs from its baseline calibrated value. In (ii), when we fix ν_{xi} to its calibrated value and increase ν_{ci}, TFP is higher at every point in time. By making consumption goods more tradables intensive, the production-possibility frontier shifts more in response to reductions in trade costs (see Figures 11a and 11b). Note that the change in TFP depends on the change in the home trade share, π_{ii}, and the value of ν_{ci}. However, the change in the home trade share is virtually invariant to the values of ν_{ci} and ν_{xi}. Therefore, the difference in the paths for TFP in country i between the two specifications is determined entirely by the value of ν_{ci}.

Similarly, the difference in the paths for the capital stock is determined by the value of ν_{xi}. When we fix ν_{xi} to its calibrated value, capital follows the same path as in the baseline model, even though ν_{ci} differs from its calibrated value. Instead, when we increase ν_{xi} to the fixed value of ν_{ci}, capital is lower at every point in time (see Figures 11c and 11d).

Figure 11: Transitions with equal tradables intensities in consumption and investment



Notes: Transitions following an unanticipated, uniform, and permanent 20 percent liberalization. The initial steady state is normalized to 1. The liberalization occurs in period 1. One specification keeps ν_{ci} fixed to its calibrated value and increases ν_{xi} to equal ν_{ci}. The other specification keeps ν_{xi} fixed to its calibrated value and decreases ν_{ci} to equal ν_{xi}.

In sum, the tradables intensity in investment goods production determines the transition path for capital and, hence, the dynamic gains; the tradables intensity in consumption goods production determines the transition path for TFP and, hence, the immediate gains.

6 Conclusion

We build a multicountry trade model with capital accumulation to study dynamic welfare gains. In our model, tradable intermediates are used in the production of final consumption goods and investment goods with different intensities. Cross-country asset trades generate endogenous trade imbalances and help smooth consumption over time.

Trade liberalization reduces the price of tradables. The intensity of tradables in the consumption goods sector dictates the magnitude of the increase in TFP, while the intensity of tradables in the investment goods sector dictates the increase in investment and capital stock. Higher TFP increases the rate of return to investment and, hence, the capital stock. Both channels affect consumption along the transition path and, hence, the welfare gains. The fall in the price of tradables also reduces the price of investment relative to consumption since investment goods are more tradables intensive than consumption goods. The decline in the relative price of investment alters the rate of transformation between consumption and investment, which boosts the share of output allocated to investment and allows countries attain higher capital-labor ratios.

For an unanticipated, uniform, and permanent reduction in trade costs, we find that the gains are negatively correlated with size; financial resources flow from larger countries to smaller countries; countries with larger short-run trade deficits accumulate capital faster; smaller countries frontload their consumption, while larger countries do the opposite; the gains are nonlinear in the reduction in trade costs; and capital accumulation delivers substantial gains relative to a model where capital is fixed.

The NFA position before the liberalization is quantitatively important for the gains. The liberalization increases the world interest rate on impact, which implies that countries with initial debt suffer and countries with initial positive assets benefit. As a result, the gain is positively correlated with the initial NFA position.

Our computational algorithm efficiently solves for the exact transitional dynamics for a system of second-order, nonlinear difference equations. Our method iterates on prices using excess demand functions and does not involve costly gradient calculations. It delivers the transition paths for all countries in about 30 minutes. Thus, our method is useful for solving multicountry trade models with large state spaces. Our solution method can also be used to analyze other changes in trade costs, such as multilateral trade agreements with gradual reductions in trade costs (e.g., the European Union), anticipated changes in trade costs (e.g., Brexit), and other models with multiple sectors and IO linkages.

With diminishing returns to capital accumulation, we have clearly abstracted from the effect of trade liberalization on long-run growth. Our model can be extended to study the gains from trade resulting from changes in the rate of long-run growth. One avenue would be to assume constant returns to capital accumulation (the so-called "Ak" model) and bound the marginal product of capital to be sufficiently far away from zero. In such a model, the trade cost affects the return to capital and, hence, the investment rate and the rate of long-run growth (see Lee, 1993), for instance, for a small open Ak economy). Another avenue would be to introduce an R&D sector into our model, as in the two-country model of Grossman and Helpman (1990). In such a model, investment in R&D expands the variety of intermediate goods, which increases TFP in the final goods sector. The investment also helps accumulate knowledge that is not subject to diminishing returns. Trade costs then affect the rates of knowledge accumulation and TFP growth. Changes in trade costs in both models affect the rate of long-run growth and, hence, the gains from trade.

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Appendix

A Equilibrium conditions

We describe each equilibrium condition in detail below.

Household optimization The representative household chooses a path for consumption that satisfies two intertemporal Euler equations associated with the one-period bond and capital:

$$\frac{c_{it+1}}{c_{it}} = \beta^{\sigma} \left(\frac{1 + q_{t+1}}{P_{cit+1}/P_{cit}} \right)^{\sigma}$$

and

$$\frac{c_{it+1}}{c_{it}} = \beta^{\sigma} \left(\frac{\frac{r_{it+1}}{P_{ixt+1}} - \Phi_2(k_{it+2}, k_{it+1})}{\Phi_1(k_{it+1}, k_{it})} \right)^{\sigma} \left(\frac{P_{xit+1}/P_{cit+1}}{P_{xit}/P_{cit}} \right)^{\sigma},$$

where $\Phi_1(\cdot, \cdot)$ and $\Phi_2(\cdot, \cdot)$ denote the first derivatives of the adjustment-cost function with respect to the first and second arguments, respectively:

$$\Phi_1(k', k) = \delta^{\frac{\lambda-1}{\lambda}} \left(\frac{1}{\lambda} \right) \left(\frac{k'}{k} - (1 - \delta) \right)^{\frac{1-\lambda}{\lambda}}$$
$$\Phi_2(k', k) = \delta^{\frac{\lambda-1}{\lambda}} \left(\frac{1}{\lambda} \right) \left(\frac{k'}{k} - (1 - \delta) \right)^{\frac{1-\lambda}{\lambda}} \left((\lambda - 1)\frac{k'}{k} - \lambda(1 - \delta) \right).$$

Combining the household's budget constraint and the capital accumulation technology and rearranging, we get

$$P_{cit}C_{it} + P_{xit}\Phi(K_{it+1}, K_{it}) + \mathcal{A}_{it+1} = r_{it}K_{it} + w_{it}L_i + q_t\mathcal{A}_{it}.$$

Firm optimization Markets are perfectly competitive, so firms set prices equal to marginal costs. Denote the price of variety v produced in country j and purchased by country i as $p_{mij}(v)$. Then $p_{mij}(v) = p_{mjj}(v)d_{ij}$; in country j, $p_{mjj}(v)$ is also the marginal cost of producing variety v. Since country i purchases each variety from the country that can deliver it at the lowest price, the price in country i is $p_{mi}(v) = \min_{j=1,\ldots,I}[p_{mjj}(v)d_{mij}]$.

The price of the composite good in country i at time t is then

$$P_{mit} = \gamma \left[\sum_{j=1}^{I} (u_{jt} d_{ij})^{-\theta} T_{mj} \right]^{-\frac{1}{\theta}},$$

where $u_{jt} = \left(\frac{r_{jt}}{\alpha\nu_{mj}}\right)^{\alpha\nu_{mj}} \left(\frac{w_{jt}}{(1-\alpha)\nu_{mj}}\right)^{(1-\alpha)\nu_{mj}} \left(\frac{P_{jt}}{1-\nu_{mj}}\right)^{1-\nu_{mj}}$ is the unit cost for a bundle of inputs for intermediate goods producers in country n at time t.

Next we define total factor usage in the intermediates sector by aggregating across the individual varieties:

$$K_{mit} = \int_0^1 K_{mit}(v)dv, \qquad L_{mit} = \int_0^1 L_{mit}(v)dv,$$
$$M_{mit} = \int_0^1 M_{mit}(v)dv, \qquad Y_{mit} = \int_0^1 Y_{mit}(v)dv.$$

The term $L_{mit}(v)$ denotes the labor used in the production of variety v at time t. If country i imports variety v at time t, then $L_{mit}(v) = 0$. Hence, L_{mit} is the total labor used in sector m in country i at time t. Similarly, K_{mit} is the total capital used, M_{mit} is the total intermediates used as an input, and Y_{mit} is the total output of intermediates.

Cost minimization by firms implies that, within each sector $b \in \{c, m, x\}$, factor expenses exhaust the value of output:

$$\begin{aligned} r_{it} K_{bit} &= \alpha\nu_{bi} P_{bit} Y_{bit}, \\ w_{it} L_{bit} &= (1-\alpha)\nu_{bi} P_{bit} Y_{bit}, \\ P_{mit} M_{bit} &= (1-\nu_{bi}) P_{bit} Y_{bit}. \end{aligned}$$

That is, the fraction $\alpha\nu_{bi}$ of the value of each sector's production compensates capital services, the fraction $(1-\alpha)\nu_{bi}$ compensates labor services, and the fraction $1-\nu_{bi}$ covers the cost of intermediate inputs; there are zero profits.

Trade flows The fraction of country i's expenditures allocated to intermediate varieties produced by country j is given by

$$\pi_{ijt} = \frac{(u_{mjt} d_{ijt})^{-\theta} T_{mj}}{\sum_{j=1}^{I} (u_{mjt} d_{ij})^{-\theta} T_{mj}},$$

where u_{mjt} is the unit cost of intermediate varieties in country j.

Market clearing The domestic factor market-clearing conditions are

$$\sum_{b\in\{c,m,x\}} K_{bit} = K_{it}, \qquad \sum_{b\in\{c,m,x\}} L_{bit} = L_i, \qquad \sum_{b\in\{c,m,x\}} M_{bit} = M_{it}.$$

The first two conditions impose that the capital and labor markets clear in country i at each time t. The third condition requires that the use of the composite good equals its supply. Its use consists of demand by firms in each sector. Its supply consists of both domestically and foreign-produced varieties.

The next set of conditions require that goods markets clear:

$$C_{it} = Y_{cit}, \qquad X_{it} = Y_{xit}, \qquad \sum_{j=1}^{I} P_{mjt}\left(M_{cjt} + M_{mjt} + M_{xjt}\right)\pi_{jit} = P_{mit}Y_{mit}.$$

The first condition states that the quantity of (nontradable) consumption demanded by the representative household in country i must equal the quantity produced by country i. The second condition states the same for the investment good. The third condition imposes that the value of intermediates produced by country i has to be absorbed globally. Recall that $P_{mjt}M_{bjt}$ is the value of intermediate inputs that country i uses in production in sector b. The term π_{jit} is the fraction of country j's intermediate good expenditures sourced from country i. Therefore, $P_{mjt}M_{bjt}\pi_{jit}$ denotes the value of trade flows from country i to j.

Finally, we impose the balance-of-payments constraint in each country:

$$B_{it} = P_{mit}Y_{mit} - P_{mit}M_{it} + q_t\mathcal{A}_{it}.$$

Given an initial NFA position and capital stock, the equilibrium transition path consists of the following objects: $\{\vec{w}_t\}_{t=1}^T$, $\{\vec{r}_t\}_{t=1}^T$, $\{q_t\}_{t=1}^T$, $\{\vec{P}_{ct}\}_{t=1}^T$, $\{\vec{P}_{mt}\}_{t=1}^T$, $\{\vec{P}_{xt}\}_{t=1}^T$, $\{\vec{C}_t\}_{t=1}^T$, $\{\vec{X}_t\}_{t=1}^T$, $\{\vec{K}_t\}_{t=1}^{T+1}$, $\{\vec{B}_t\}_{t=1}^T$, $\{\vec{\mathcal{A}}_t\}_{t=1}^{T+1}$, $\{\vec{Y}_{ct}\}_{t=1}^T$, $\{\vec{Y}_{mt}\}_{t=1}^T$, $\{\vec{Y}_{xt}\}_{t=1}^T$, $\{\vec{K}_{ct}\}_{t=1}^T$, $\{\vec{K}_{mt}\}_{t=1}^T$, $\{\vec{K}_{xt}\}_{t=1}^T$, $\{\vec{L}_{ct}\}_{t=1}^T$, $\{\vec{L}_{mt}\}_{t=1}^T$, $\{\vec{L}_{xt}\}_{t=1}^T$, $\{\vec{M}_{ct}\}_{t=1}^T$, $\{\vec{M}_{mt}\}_{t=1}^T$, $\{\vec{M}_{xt}\}_{t=1}^T$, $\{\vec{\vec{\pi}}_t\}_{t=1}^T$. (The double-arrow notation on $\vec{\vec{\pi}}_t$ is used to indicate that this is an $I \times I$ matrix in each period t.) Table A.1 provides a list of equilibrium conditions that these objects must satisfy.

In this environment, the world interest rate is strictly nominal. That is, the prices map into current units, as opposed to constant units. In other words, the model can be rewritten so that all prices are quoted in time-1 units (like in an Arrow-Debreu world), with the world

Table A.1: Dynamic equilibrium conditions

1	$r_{it}K_{cit} = \alpha\nu_{ci}P_{cit}Y_{cit}$	$\forall(i,t)$
2	$r_{it}K_{mit} = \alpha\nu_{mi}P_{mit}Y_{mit}$	$\forall(i,t)$
3	$r_{it}K_{xit} = \alpha\nu_{xi}P_{xit}Y_{xit}$	$\forall(i,t)$
4	$w_{it}L_{cit} = (1-\alpha)\nu_{ci}P_{cit}Y_{cit}$	$\forall(i,t)$
5	$w_{it}L_{mit} = (1-\alpha)\nu_{mi}P_{mit}Y_{mit}$	$\forall(i,t)$
6	$w_{it}L_{xit} = (1-\alpha)\nu_{xi}P_{xit}Y_{xit}$	$\forall(i,t)$
7	$P_{mit}M_{cit} = (1-\nu_{ci})P_{cit}Y_{cit}$	$\forall(i,t)$
8	$P_{mit}M_{mit} = (1-\nu_{mi})P_{mit}Y_{mit}$	$\forall(i,t)$
9	$P_{mit}M_{xit} = (1-\nu_{xi})P_{xit}Y_{xit}$	$\forall(i,t)$
10	$K_{cit} + K_{mit} + K_{xit} = K_{it}$	$\forall(i,t)$
11	$L_{cit} + L_{mit} + L_{xit} = L_{it}$	$\forall(i,t)$
12	$M_{cit} + M_{mit} + M_{xit} = M_{it}$	$\forall(i,t)$
13	$C_{it} = Y_{cit}$	$\forall(i,t)$
14	$\sum_{j=1}^{I} P_{mjt}M_{jt}\pi_{jit} = P_{mit}Y_{mit}$	$\forall(i,t)$
15	$X_{it} = Y_{xit}$	$\forall(i,t)$
16	$P_{cit} = \left(\frac{1}{A_{ci}}\right)\left(\frac{r_{it}}{\alpha\nu_{ci}}\right)^{\alpha\nu_{ci}}\left(\frac{w_{it}}{(1-\alpha)\nu_{ci}}\right)^{(1-\alpha)\nu_{ci}}\left(\frac{P_{mit}}{1-\nu_{ci}}\right)^{1-\nu_{ci}}$	$\forall(i,t)$
17	$P_{mit} = \gamma\left[\sum_{j=1}^{I}(u_{mjt}d_{ijt})^{-\theta}T_{mjt}\right]^{-\frac{1}{\theta}}$	$\forall(i,t)$
18	$P_{xit} = \left(\frac{1}{A_{xi}}\right)\left(\frac{r_{it}}{\alpha\nu_{xi}}\right)^{\alpha\nu_{xi}}\left(\frac{w_{it}}{(1-\alpha)\nu_{xi}}\right)^{(1-\alpha)\nu_{xi}}\left(\frac{P_{mit}}{1-\nu_{xi}}\right)^{1-\nu_{xi}}$	$\forall(i,t)$
19	$\pi_{ijt} = \frac{(u_{mjt}d_{ijt})^{-\theta}T_{mjt}}{\sum_{j=1}^{I}(u_{mjt}d_{ijt})^{-\theta}T_{mjt}}$	$\forall(i,j,t)$
20	$P_{cit}C_{it} + P_{xit}X_{it} + B_{it} = r_{it}K_{it} + w_{it}L_{it} + q_t\mathcal{A}_{it}$	$\forall(i,t)$
21	$\mathcal{A}_{it+1} = \mathcal{A}_{it} + B_{it}$	$\forall(i,t)$
22	$K_{it+1} = (1-\delta)K_{it} + \delta^{1-\lambda}X_{it}^{\lambda}K_{it}^{1-\lambda}$	$\forall(i,t)$
23	$\frac{c_{it+1}}{c_{it}} = \beta^{\sigma}\left(\frac{\frac{r_{it+1}}{P_{xit+1}} - \Phi_2(k_{it+2},k_{it+1})}{\Phi_1(k_{it+1},k_{it})}\right)^{\sigma}\left(\frac{P_{xit+1}/P_{cit+1}}{P_{xit}/P_{cit}}\right)^{\sigma}$	$\forall(i,t)$
24	$\frac{c_{it+1}}{c_{it}} = \beta^{\sigma}\left(\frac{1+q_{t+1}}{P_{cit+1}/P_{cit}}\right)^{\sigma}$	$\forall(i,t)$
25	$B_{it} = P_{mit}Y_{mit} - P_{mit}M_{it} + q_t\mathcal{A}_{it}$	$\forall(i,t)$

Note: The term $u_{mjt} = \left(\frac{r_{jt}}{\alpha\nu_m}\right)^{\alpha\nu_m}\left(\frac{w_{jt}}{(1-\alpha)\nu_m}\right)^{(1-\alpha)\nu_m}\left(\frac{P_{mjt}}{1-\nu_m}\right)^{1-\nu_m}$. In our notation, $c = C/L$ and $k = K/L$.

interest rate of zero and the equilibrium yielding identical quantities. Since our choice of numéraire is world GDP in each period, the world interest rate reflects the relative valuation of world GDP at two points in time. This interpretation helps guide the solution procedure.

In general, in models with trade imbalances, the steady state is not independent of the transition path. We treat the initial steady state as independent of the prior transition by fixing the NFA position. With this NFA, all other steady-state equilibrium conditions are pinned down uniquely. The new steady state is determined jointly with the transition path. The solution to the initial steady-state consists of 23 objects: $\vec{w}^\star$, $\vec{r}^\star$, $q^\star$, $\vec{P}_c^\star$, $\vec{P}_m^\star$, $\vec{P}_x^\star$, $\vec{C}^\star$, $\vec{X}^\star$, $\vec{K}^\star$, $\vec{M}^\star$, $\vec{Y}_c^\star$, $\vec{Y}_m^\star$, $\vec{Y}_x^\star$, $\vec{K}_c^\star$, $\vec{K}_m^\star$, $\vec{K}_x^\star$, $\vec{L}_c^\star$, $\vec{L}_m^\star$, $\vec{L}_x^\star$, $\vec{M}_c^\star$, $\vec{M}_m^\star$, $\vec{M}_x^\star$, $\vec{\vec{\pi}}^\star$ (we use the double-arrow notation on $\vec{\vec{\pi}}_t$ to indicate that this is an $I \times I$ matrix). Table A.2 provides a list of 24 conditions that these objects must satisfy. One market-clearing equation is redundant (condition 12 in our algorithm).

B Derivations of structural relationships

This appendix shows the derivations of key structural relationships. We refer to Table A.1 for the derivations and omit time subscripts to simplify notation. We begin by deriving an expression for $\frac{w_i}{P_{mi}}$ that will be used repeatedly.

Combining conditions 17 and 19, we obtain

$$\pi_{ii} = \gamma^{-\theta} \left(\frac{u_{mi}^{-\theta} T_{mi}}{P_{mi}^{-\theta}} \right).$$

Use the fact that $u_{mi} = B_{mi} r_i^{\alpha\nu_{mi}} w_i^{(1-\alpha)\nu_{mi}} P_{mi}^{1-\nu_{mi}}$, where B_{mi} is a collection of country-specific constants, and rearrange to obtain

$$P_{mi} = \left(\frac{T_{mi}}{\pi_{ii}} \right)^{-\frac{1}{\theta}} \left(\frac{r_i}{w_i} \right)^{\alpha\nu_{mi}} \left(\frac{w_i}{P_{mi}} \right)^{\nu_{mi}} P_{mi}$$

$$\Rightarrow \frac{w_i}{P_{mi}} = \left(\frac{\left(\frac{T_{mi}}{\pi_{ii}} \right)^{\frac{1}{\theta}}}{\gamma B_{mi}} \right)^{\frac{1}{\nu_{mi}}} \left(\frac{w_i}{r_i} \right)^{\alpha}. \tag{B.1}$$

Note that this relationship holds in both the steady state and along the transition.

Table A.2: Steady-state conditions

1	$r_i^\star K_{ci}^\star = \alpha\nu_{ci} P_{ci}^\star Y_{ci}^\star$	$\forall(i)$
2	$r_i^\star K_{mi}^\star = \alpha\nu_{mi} P_{mi}^\star Y_{mi}^\star$	$\forall(i)$
3	$r_i^\star K_{xi}^\star = \alpha\nu_{xi} P_{xi}^\star Y_{xi}^\star$	$\forall(i)$
4	$w_i^\star L_{ci}^\star = (1-\alpha)\nu_{ci} P_{ci}^\star Y_{ci}^\star$	$\forall(i)$
5	$w_i^\star L_{mi}^\star = (1-\alpha)\nu_{mi} P_{mi}^\star Y_{mi}^\star$	$\forall(i)$
6	$w_i^\star L_{xi}^\star = (1-\alpha)\nu_{xi} P_{xi}^\star Y_{xi}^\star$	$\forall(i)$
7	$P_{mi}^\star M_{ci}^\star = (1-\nu_{ci}) P_{ci}^\star Y_{ci}^\star$	$\forall(i)$
8	$P_{mi}^\star M_{mi}^\star = (1-\nu_{mi}) P_{mi}^\star Y_{mi}^\star$	$\forall(i)$
9	$P_{mi}^\star M_{xi}^\star = (1-\nu_{xi}) P_{xi}^\star Y_{xi}^\star$	$\forall(i)$
10	$K_{ci}^\star + K_{mi}^\star + K_{xi}^\star = K_i^\star$	$\forall(i)$
11	$L_{ci}^\star + L_{mi}^\star + L_{xi}^\star = L_i$	$\forall(i)$
12	$M_{ci}^\star + M_{mi}^\star + M_{xi}^\star = M_i^\star$	$\forall(i)$
13	$C_i^\star = Y_{ci}^\star$	$\forall(i)$
14	$\sum_{j=1}^{I} P_{mj}^\star \left(M_{cj}^\star + M_{mj}^\star + M_{xj}^\star\right) \pi_{ji} = P_{mi}^\star Y_{mi}^\star$	$\forall(i)$
15	$X_i^\star = Y_{xi}^\star$	$\forall(i)$
16	$P_{ci}^\star = \left(\frac{1}{A_{ci}}\right)\left(\frac{r_i^\star}{\alpha\nu_{ci}}\right)^{\alpha\nu_{ci}}\left(\frac{w_i^\star}{(1-\alpha)\nu_{ci}}\right)^{(1-\alpha)\nu_{ci}}\left(\frac{P_{mi}^\star}{1-\nu_{ci}}\right)^{1-\nu_{ci}}$	$\forall(i)$
17	$P_{mi}^\star = \gamma\left[\sum_{j=1}^{I}(u_{mj}^\star d_{ij})^{-\theta} T_{mj}\right]^{-\frac{1}{\theta}}$	$\forall(i)$
18	$P_{xi}^\star = \left(\frac{1}{A_{xi}}\right)\left(\frac{r_i^\star}{\alpha\nu_{xi}}\right)^{\alpha\nu_{xi}}\left(\frac{w_i^\star}{(1-\alpha)\nu_{xi}}\right)^{(1-\alpha)\nu_{xi}}\left(\frac{P_{mi}^\star}{1-\nu_{xi}}\right)^{1-\nu_{xi}}$	$\forall(i)$
19	$\pi_{ij}^\star = \frac{(u_{mj}^\star d_{ij})^{-\theta} T_{mj}}{\sum_{j=1}^{I}(u_{mj}^\star d_{ij})^{-\theta} T_{mj}}$	$\forall(i,j)$
20	$0 = P_{mi}^\star\left(Y_{mi}^\star - M_i^\star\right) + q^\star \mathcal{A}_i$	$\forall(i)$
21	$P_{ci}^\star C_i^\star + P_{xi}^\star X_i^\star = r_i^\star K_i^\star + w_i^\star L_i^\star + q^\star \mathcal{A}_i$	$\forall(i)$
22	$X_i^\star = \delta K_i^\star$	$\forall(i)$
23	$r_i^\star = \left(\frac{\Phi_{1i}^\star}{\beta} + \Phi_{2i}^\star\right) P_{xi}^\star$	$\forall(i)$
24	$q^\star = 1/\beta - 1$	

Notes: $u_{mj}^\star = \left(\frac{r_j^\star}{\alpha\nu_m}\right)^{\alpha\nu_m}\left(\frac{w_j^\star}{(1-\alpha)\nu_m}\right)^{(1-\alpha)\nu_m}\left(\frac{P_{mj}^\star}{1-\nu_m}\right)^{1-\nu_m}$. The steady-state level of the NFA position, $\mathcal{A}_i$, is indeterminate and must be solved for jointly with the entire transition path. Once a steady state is reached, these conditions hold. For the initial steady state, we target net exports and pin down $\mathcal{A}_i$ using condition 20. We cannot do this in the counterfactual.

Relative prices We show how to derive the price of consumption relative to intermediates; the relative price of investment is analogous. Begin with condition 16 to obtain

$$P_{ci} = \left(\frac{B_{ci}}{A_{ci}}\right)\left(\frac{r_i}{w_i}\right)^{\alpha\nu_{ci}}\left(\frac{w_i}{P_{mi}}\right)^{\nu_{ci}} P_{mi},$$

where B_{ci} is a collection of country-specific constants. Substitute equation (B.1) into the previous expression and rearrange to obtain

$$\frac{P_{ci}}{P_{mi}} = \left(\frac{B_{ci}}{A_{ci}}\right)\left(\frac{\left(\frac{T_{mi}}{\pi_{ii}}\right)^{\frac{1}{\theta}}}{\gamma B_{mi}}\right)^{\frac{\nu_{ci}}{\nu_{mi}}}. \tag{B.2}$$

Analogously,

$$\frac{P_{xi}}{P_{mi}} = \left(\frac{B_{xi}}{A_{xi}}\right)\left(\frac{\left(\frac{T_{mi}}{\pi_{ii}}\right)^{\frac{1}{\theta}}}{\gamma B_{mi}}\right)^{\frac{\nu_{xi}}{\nu_{mi}}}. \tag{B.3}$$

Note that these relationships hold in both the steady state and along the transition.

Income per worker We define (real) income per worker in our model as

$$y_i = \frac{r_i K_i + w_i L_i}{L_i P_{ci}}.$$

We invoke conditions from Table A.1 for the remainder of this derivation. Conditions 1-6, 10, and 11 imply that

$$\begin{aligned} r_i K_i + w_i L_i &= \frac{w_i L_i}{1-\alpha} \\ \Rightarrow y_i &= \left(\frac{1}{1-\alpha}\right)\left(\frac{w_i}{P_{ci}}\right). \end{aligned}$$

To solve for $\frac{w_i}{P_{ci}}$, we use condition 16:

$$\begin{aligned} P_{ci} &= \frac{B_{ci}}{A_{ci}}\left(\frac{r_i}{w_i}\right)^{\alpha\nu_{ci}}\left(\frac{w_i}{P_{mi}}\right)^{\nu_{ci}} P_{mi} \\ \Rightarrow \frac{P_{ci}}{w_i} &= \frac{B_{ci}}{A_{ci}}\left(\frac{r_i}{w_i}\right)^{\alpha\nu_{ci}}\left(\frac{w_i}{P_{mi}}\right)^{\nu_{ci}-1}. \end{aligned}$$

Substituting equation (B.1) into the previous expression and exploiting the fact that $\frac{w_i}{r_i} = \left(\frac{1-\alpha}{\alpha}\right)\left(\frac{K_i}{L_i}\right)$ yields

$$
\begin{aligned}
y_i &= \left(\frac{1}{1-\alpha}\right)\left(\frac{w_i}{P_{ci}}\right) \\
&= \alpha^{-\alpha}\left(1-\alpha\right)^{\alpha-1}\left(\frac{A_{ci}}{B_{ci}}\right)\left(\frac{\left(\frac{T_{mi}}{\pi_{ii}}\right)^{\frac{1}{\theta}}}{B_{mi}}\right)^{\frac{1-\nu_{ci}}{\theta\nu_{mi}}}\left(\frac{K_i}{L_i}\right)^{\alpha}. \qquad \text{(B.4)}
\end{aligned}
$$

Steady-state capital-labor ratio and income We derive a structural relationship for the capital-labor ratio in the steady state only and refer to the conditions in Table A.2. Conditions 1-6 together with conditions 10 and 11 imply that

$$\frac{K_i}{L_i} = \left(\frac{\alpha}{1-\alpha}\right)\left(\frac{w_i}{r_i}\right).$$

Using condition 23, we know that

$$r_i = \left(\frac{\Phi_1}{\beta} + \Phi_2\right) P_{xi},$$

which, by substituting into the prior expression, implies that

$$\frac{K_i}{L_i} = \left(\frac{\alpha}{\left(1-\alpha\right)\left(\frac{\Phi_1}{\beta} + \Phi_2\right)}\right)\left(\frac{w_i}{P_{xi}}\right),$$

which leaves the problem of solving for $\frac{w_i}{P_{xi}}$. Equations (B.1) and (B.3) imply

$$\frac{w_i}{P_{xi}} = \left(\frac{w_i}{P_{mi}}\right)\left(\frac{P_{mi}}{P_{xi}}\right) = \left(\frac{A_{xi}}{B_{xi}}\right)\left(\frac{\left(\frac{T_{mi}}{\pi_{ii}}\right)^{\frac{1}{\theta}}}{\gamma B_{mi}}\right)^{\frac{1-\nu_{xi}}{\nu_{mi}}}\left(\frac{w_i}{r_i}\right)^{\alpha}.$$

Substituting once more for $\frac{w_i}{r_i}$ in the previous expression yields

$$\left(\frac{w_i}{P_{xi}}\right)^{1-\alpha} = \left(\frac{\Phi_1}{\beta} + \Phi_2\right)^{-\alpha}\left(\frac{A_{xi}}{B_{xi}}\right)\left(\frac{\left(\frac{T_{mi}}{\pi_{ii}}\right)^{\frac{1}{\theta}}}{\gamma B_{mi}}\right)^{\frac{1-\nu_{xi}}{\nu_{mi}}}.$$

Solve for the aggregate capital-labor ratio:

$$\frac{K_i}{L_i} = \left(\frac{\frac{\alpha}{1-\alpha}}{\left(\frac{\Phi_1}{\beta} + \Phi_2\right)^{-\frac{1}{1-\alpha}}} \right) \left(\frac{A_{xi}}{B_{xi}}\right)^{\frac{1}{1-\alpha}} \left(\frac{\left(\frac{T_{mi}}{\pi_{ii}}\right)^{\frac{1}{\theta}}}{\gamma B_{mi}} \right)^{\frac{1-\nu_{xi}}{(1-\alpha)\nu_{mi}}} . \tag{B.5}$$

The steady-state income per worker, by invoking equation (B.5), can be expressed as

$$y_i = \left(\frac{\left(\frac{\Phi_1}{\beta} + \Phi_2\right)^{-\frac{\alpha}{1-\alpha}}}{1-\alpha} \right) \left(\frac{A_{ci}}{B_{ci}}\right) \left(\frac{A_{xi}}{B_{xi}}\right)^{\frac{\alpha}{1-\alpha}} \left(\frac{\left(\frac{T_{mi}}{\pi_{ii}}\right)^{\frac{1}{\theta}}}{\gamma B_{mi}} \right)^{\frac{1-\nu_{ci}+\frac{\alpha}{1-\alpha}(1-\nu_{xi})}{\nu_{mi}}} . \tag{B.6}$$

Note that we invoked steady-state conditions, so this expression does not necessarily hold along the transition path.

C Data

This section describes the sources of data and any adjustments we make to the data to map it to the model. The primary data sources include version 9.0 of the PWT, the WIOD, and the CEPII. Our data include 44 regions: 43 countries and ROW (see Table C.1).

Production and trade We map the sectors in our model to the sectors in the data using two-digit categories in revision 3 of the ISIC. The intermediates correspond to categories 01-28; the investment sector corresponds to ISIC categories 29-35 and 45; and the consumption sector corresponds to the remaining categories.

Both value added and gross output for each of the three sectors are obtained directly from the WIOD using the above classification.

We construct bilateral trade data by aggregating observed trade in categories 01-28. Using the trade and production data, we construct bilateral trade shares for each country pair by following Bernard, Eaton, Jensen, and Kortum (2003): $\pi_{ij} = \frac{X_{ij}}{ABS_{bi}}$, where i denotes the importer, j denotes the exporter, X_{ij} denotes manufacturing trade flows from j to i, and ABS_i denotes country i's absorption defined as gross output less net exports of manufactures.

GDP, employment and prices We use data on output-side real GDP at current purchasing power parity (PPP) from PWT using the variable `cgdpo`. We convert this data

Table C.1: List of countries

ISO code	Country	ISO code	Country
AUS	Australia	IRL	Ireland
AUT	Austria	ITA	Italy
BEL	Belgium	JPN	Japan
BGR	Bulgaria	KOR	South Korea
BRA	Brazil	LTU	Lithuania
CAN	Canada	LUX	Luxembourg
CHE	Switzerland	LVA	Latvia
CHN	China	MEX	Mexico
CYP	Cyprus	MLT	Malta
CZE	Czech Republic	NLD	Netherlands
DEU	Germany	NOR	Norway
DNK	Denmark	POL	Poland
ESP	Spain	PRT	Potugal
EST	Estonia	ROU	Romania
FIN	Finland	RUS	Russia
FRA	France	SVK	Slovakia
GBR	United Kingdom	SVN	Slovenia
GRC	Greece	SWE	Sweden
HRV	Croatia	TUR	Turkey
HUN	Hungary	TWN	Taiwan
IDN	Indonesia	USA	United States
IND	India	ROW	Rest of the World

Notes: ISO, International Organization for Standardization.

into U.S. dollars at market exchange rates by multiplying it by the price level of GDP at PPP, which is `pl_gdpo` in PWT. We use the variable `emp` from PWT to measure the employment in each country. Our measure of real income is GDP at market exchange rates divided by the price level of consumption at PPP exchange rates, which is variable `pl_c` in the PWT, and corresponds to P_c in our model. The ratio $\frac{\texttt{cgdpo*pl\_gdpo}}{\texttt{pl\_c*emp}}$ corresponds to GDP per worker, y, in our model.

The price of investment is obtained from PWT using variable `pl_i`. This corresponds to P_x in our model.

We construct the price of tradable intermediate goods (manufactures) taking the average, for each country, of the price level of imports and the price level of exports, `pl_m` and `pl_x`, respectively, in PWT. This corresponds to P_m in our model.

D Solution algorithm

In this appendix, we describe the algorithm for computing (i) the initial steady state and (ii) the transition path. Before going further into the algorithms, we introduce some notation. We denote the steady-state objects by a superscript $\star$; that is, $K_i^\star$ is the steady-state capital stock in country i. We denote the vector of capital stocks at time t as $\vec{K}_t = \{K_{it}\}_{i=1}^I$.

D.1 Computing the initial steady state

We use the technique from Mutreja, Ravikumar, and Sposi (2018), which builds on Alvarez and Lucas (2007), to solve for the steady state. The idea is to guess a vector of wages, then recover all remaining prices and quantities using optimality conditions and market-clearing conditions, excluding the balance-of-payments condition. We then use departures from the balance-of-payments condition in each country to update our wage vector and iterate until we find a wage vector that satisfies the balance-of-payments condition. The following steps outline our procedure in more detail:

(i) We guess a vector of wages $\vec{w} \in \Delta = \{w \in \mathbb{R}_+^I : \sum_{i=1}^I \frac{w_i L_i}{1-\alpha} = 1\}$, that is, with world GDP as the numéraire.

(ii) We compute prices $\vec{P}_c, \vec{P}_x, \vec{P}_m$, and $\vec{r}$ simultaneously using conditions 16, 17, 18, and 23 in Table A.2. The steady-state world interest rate is given by condition 24. To complete this step, we compute the bilateral trade shares $\vec{\vec{\pi}}$ using condition 19.

(iii) We compute the aggregate capital stock as $K_i = \frac{\alpha}{1-\alpha} \frac{w_i L_i}{r_i}$ for all i, which is easily derived from optimality conditions 1 and 4, 2 and 5, and 3 and 6, coupled with market-clearing conditions for capital and labor, 10 and 11 in Table A.2.

(iv) We use condition 22 to solve for steady-state investment $\vec{X}$. Then we use condition 21 to solve for steady-state consumption $\vec{C}$.

(v) We combine conditions 4 and 13 to solve for $\vec{L}_c$, 5 and 14 to solve for $\vec{L}_x$, and use 11 to solve for $\vec{L}_m$. Next we combine conditions 1 and 4 to solve for $\vec{K}_c$, 2 and 5 to solve for $\vec{K}_M$, and 3 and 6 to solve for $\vec{K}_x$. Similarly, we combine conditions 4 and 7 to solve for $\vec{M}_c$, 5 and 8 to solve for $\vec{M}_m$, and 6 and 9 to solve for $\vec{M}_x$.

(vi) We compute $\vec{Y}_c$ using condition 13, compute $\vec{Y}_m$ using condition 14, and compute $\vec{Y}_x$ using condition 15.

(vii) We compute an excess demand as in Alvarez and Lucas (2007):

$$Z_i(\vec{w}) = \frac{P_{mi}Y_{mi} - P_{mi}M_i + q^\star \mathcal{A}_i}{w_i}$$

(the current account balance relative to the wage). Condition 20 requires that $Z_i(\vec{w}) = 0$ for all i. If the excess demand is sufficiently close to 0, then we have a steady state. If not, we update the wage vector using the excess demand as follows:

$$\Lambda_i(\vec{w}) = w_i \left(1 + \psi \frac{Z_i(\vec{w})}{L_i}\right),$$

where ψ is chosen to be sufficiently small so that $\Lambda > 0$. Note that $\sum_{i=1}^{I} \frac{\Lambda_i(\vec{w})L_i}{1-\alpha} = \sum_{i=1}^{I} \frac{w_i L_i}{1-\alpha} + \psi \sum_{i=1}^{I} w_i Z_i(\vec{w})$. As in Alvarez and Lucas (2007), it is easy to show that $\sum_{i=1}^{I} w_i Z_i(\vec{w}) = 0$, which implies that $\sum_{i=1}^{I} \frac{\Lambda_i(\vec{w})L_i}{1-\alpha} = 1$, and hence, $\Lambda : \Delta \to \Delta$. We return to step (ii) with our updated wage vector and repeat the steps. We iterate through this procedure until the excess demand is sufficiently close to 0. In our computations we find that our preferred convergence metric,

$$\max_{i=1}^{I} \{|Z_i(\vec{w})|\},$$

converges roughly monotonically toward 0.

D.2 Computing the transition path

The solution procedure boils down to two loops. First, we guess a set of nominal investment rates at each point in time for every country. Given these investment rates, we adapt the algorithm of Sposi (2012) and iterate on the wages and the world interest rate to pin down the endogenous trade imbalances. Then we go back and update the nominal investment rates that satisfy the Euler equation for the optimal rate of capital accumulation.

To begin, we take the initial capital stock, K_{i1}, and the initial NFA position, $\mathcal{A}_{i1}$, as given in each country.

(i) Guess a path for nominal investment rates $\{\vec{\rho}_t\}_{t=1}^{T}$ and terminal NFA, $\vec{\mathcal{A}}_{T+1}$.

(ii) Guess the entire path for wages $\{\vec{w}_t\}_{t=1}^{T}$ and the world interest rate $\{q_t\}_{t=2}^{T}$ such that $\sum_i \frac{w_{it}L_{it}}{1-\alpha} = 1\,(\forall t)$.

(iii) In period 1, set $\vec{r}_1 = \left(\frac{\alpha}{1-\alpha}\right)\left(\frac{\vec{w}_1\vec{L}}{\vec{K}_1}\right)$ since the initial stock of capital is predetermined. Compute prices P_{c1}, P_{x1}, and P_{m1} simultaneously using conditions 16, 17, and 18 in Table A.1. Solve for investment, X_1, using

$$X_{it} = \rho_{it}\frac{w_{it}L_{it} + r_{it}K_{it}}{P_{xit}},$$

and then solve for the next-period capital stock, K_2, using condition 22. Repeat this set of calculations for period 2, then for period 3, and continue all the way through period T. To complete this step, compute the bilateral trade shares $\{\vec{\vec{\pi}}_t\}_{t=1}^{T}$ using condition 19.

(iv) Computing the path for consumption and bond purchases is slightly more involved. This requires solving the intertemporal problem of the household. This is done in three steps. First, we derive the lifetime budget constraint. Second, we derive the fraction of lifetime wealth allocated to consumption in each period. And third, we recover the sequences for bond purchases and the stock of NFAs.

Deriving the lifetime budget constraint To begin, (omitting country subscripts for now) use the representative household's period budget constraint in condition 20 and combine it with the NFA accumulation technology in condition 21 to get

$$\mathcal{A}_{t+1} = r_tK_t + w_tL_t - P_{ct}C_t - P_{xt}X_t + (1 + q_t)\mathcal{A}_t.$$

Iterate the period budget constraint forward through time and derive a lifetime budget constraint. At time $t = 1$, the NFA position, A_{i1}, is given. Next, compute the NFA position at time $t = 2$:

$$\mathcal{A}_2 = r_1K_1 + w_1L_1 - P_{c1}C_1 - P_{x1}X_1 + (1 + q_1)\mathcal{A}_1.$$

Similarly, compute the NFA position at time $t = 3$, but do it so that it is in terms of the initial NFA position:

$$\begin{aligned}
&\mathcal{A}_3 = r_2K_2 + w_2L_2 - P_{c2}C_2 - P_{x2}X_2 + (1 + q_2)\mathcal{A}_2 \\
\Rightarrow\ &\mathcal{A}_3 = r_2K_2 + w_2L_2 - P_{x2}X_2 + (1 + q_2)(r_1K_1 + w_1L_1 - P_{x1}X_1) \\
&\quad - P_{c2}C_2 - (1 + q_2)P_{c1}C_1 + (1 + q_2)(1 + q_1)\mathcal{A}_{i1}.
\end{aligned}$$

Continue to period 4 in a similar way:

$$
\begin{aligned}
&\mathcal{A}_4 = r_3 K_3 + w_3 L_3 - P_{c3} C_3 - P_{x3} X_3 + (1+q_3)\mathcal{A}_3 \\
\Rightarrow\ &\mathcal{A}_4 = r_3 K_3 + w_3 L_3 - P_{x3} X_3 \\
&\quad + (1+q_3)(r_2 K_2 + w_2 L_2 - P_{x2} X_2) + (1+q_3)(1+q_2)(r_1 K_1 + w_1 L_1 - P_{x1} X_1) \\
&\quad - P_{c3} C_3 - (1+q_3) P_{c2} C_2 - (1+q_3)(1+q_2) P_{c1} C_1 + (1+q_3)(1+q_2)(1+q_1)\mathcal{A}_1.
\end{aligned}
$$

Before proceeding, it will be useful to define $(1+\mathcal{Q}_t) \equiv \prod_{n=1}^{t}(1+q_n)$ so that

$$
\begin{aligned}
\mathcal{A}_4 = &\frac{(1+\mathcal{Q}_3)(r_3 K_3 + w_3 L_3 - P_{x3} X_3)}{(1+\mathcal{Q}_3)} + \frac{(1+\mathcal{Q}_3)(r_2 K_2 + w_2 L_2 - P_{x2} X_2)}{(1+\mathcal{Q}_2)} \\
&+ \frac{(1+\mathcal{Q}_3)(r_1 K_1 + w_1 L_1 - P_{x1} X_1)}{(1+\mathcal{Q}_1)} - \frac{(1+\mathcal{Q}_3) P_{c3} C_3}{(1+\mathcal{Q}_3)} \\
&- \frac{(1+\mathcal{Q}_3) P_{c2} C_2}{(1+\mathcal{Q}_2)} - \frac{(1+\mathcal{Q}_3) P_{c1} C_1}{(1+\mathcal{Q}_1)} + (1+\mathcal{Q}_3)\mathcal{A}_1.
\end{aligned}
$$

By induction, for any time t,

$$
\begin{aligned}
&\mathcal{A}_{t+1} = \sum_{n=1}^{t} \frac{(1+\mathcal{Q}_t)(r_n K_n + w_n L_n - P_{xn} X_n)}{(1+\mathcal{Q}_n)} - \sum_{n=1}^{t} \frac{(1+\mathcal{Q}_t) P_{cn} C_n}{(1+\mathcal{Q}_n)} + (1+\mathcal{Q}_t)\mathcal{A}_1 \\
\Rightarrow\ &\mathcal{A}_{t+1} = (1+\mathcal{Q}_t)\left(\sum_{n=1}^{t} \frac{r_n K_n + w_n L_n - P_{xn} X_n}{(1+\mathcal{Q}_n)} - \sum_{n=1}^{t} \frac{P_{cn} C_n}{(1+\mathcal{Q}_n)} + \mathcal{A}_1\right).
\end{aligned}
$$

Finally, observe the previous expression as of $t = T$ and rearrange terms to derive the lifetime budget constraint:

$$
\sum_{n=1}^{T} \frac{P_{cn} C_n}{(1+\mathcal{Q}_n)} = \underbrace{\sum_{n=1}^{T} \frac{r_n K_n + w_n L_n - P_{xn} X_n}{(1+\mathcal{Q}_n)} + \mathcal{A}_1 - \frac{\mathcal{A}_{T+1}}{(1+\mathcal{Q}_T)}}_{W}. \tag{D.1}
$$

In the lifetime budget constraint (D.1), W denotes the net present value of lifetime wealth, taking both the initial and terminal NFA positions as given.

Solving for the path of consumption Next, compute how the net present value of lifetime wealth is optimally allocated over time. The Euler equation (condition 24) implies the following relationship between consumption in any two periods t and n:

$$C_n = \left(\frac{L_n}{L_t}\right)\beta^{\sigma(n-t)}\left(\frac{1+\mathcal{Q}_n}{1+\mathcal{Q}_t}\right)^{\sigma}\left(\frac{P_{ct}}{P_{cn}}\right)^{\sigma}C_t$$
$$\Rightarrow \frac{P_{cn}C_n}{1+\mathcal{Q}_n} = \left(\frac{L_n}{L_t}\right)\beta^{\sigma(n-t)}\left(\frac{1+\mathcal{Q}_n}{1+\mathcal{Q}_t}\right)^{\sigma-1}\left(\frac{P_{ct}}{P_{cn}}\right)^{\sigma-1}\frac{P_tC_t}{1+\mathcal{Q}_t}.$$

Since equation (D.1) implies that $\sum_{n=1}^{T}\frac{P_{cin}C_{in}}{1+\mathcal{Q}_n} = W$, rearrange the previous expression (putting country subscripts back in) to obtain

$$\frac{P_{cit}C_{it}}{1+\mathcal{Q}_{it}} = \underbrace{\left(\frac{L_{it}\beta^{\sigma t}(1+\mathcal{Q}_{it})^{\sigma-1}P_{cit}^{1-\sigma}}{\sum_{n=1}^{T}L_{in}\beta^{\sigma n}(1+\mathcal{Q}_{in})^{\sigma-1}P_{cin}^{1-\sigma}}\right)}_{\xi_{it}}W_i. \tag{D.2}$$

That is, in each period, the household spends a share ξ_{it} of lifetime wealth on consumption, with $\sum_{t=1}^{T}\xi_{it} = 1$ for all i. Note that ξ_{it} depends only on prices.

Computing bond purchases and the NFA positions In period 1, take as given consumption spending, investment spending, capital income, labor income, and net income from the initial NFA position to solve for net bond purchases $\{\vec{B}_t\}_{t=1}^{T}$ using the period budget constraint in condition 20. Solve for the NFA position in period 2 using condition 21. Then given income and spending in period 2, recover the net bond purchases in period 2 and compute the NFA position for period 3. Continue this process through all points in time.

Balance of payments We impose that net exports equal the current account less net foreign income from asset holdings. That is,

$$Z_{it}^{w}\left(\{\vec{w}_t, q_t\}_{t=1}^{T}\right) = \frac{P_{mit}Y_{mit} - P_{mit}M_{it} - B_{it} + q_t\mathcal{A}_{it}}{w_{it}}.$$

Condition 25 requires that $Z_{it}^{w}\left(\{\vec{w}_t, \vec{r}_t\}_{t=1}^{T}\right) = 0$ for all (i,t) in equilibrium. If this is different from zero in some country at some point in time, update the wages as follows:

$$\Lambda_{it}^{w}\left(\{\vec{w}_t, q_t\}_{t=1}^{T}\right) = w_{it}\left(1 + \psi\frac{Z_{it}^{w}\left(\{\vec{w}_t, q_t\}_{t=1}^{T}\right)}{L_{it}}\right),$$

where ψ is chosen to be sufficiently small so that $\Lambda^w > 0$.

Normalizing model units The next part of this step is updating the equilibrium world interest rate. Recall that the numéraire is world GDP at each point in time: $\sum_{i=1}^{I}(r_{it}K_{it} + w_{it}L_{it}) = 1$ $(\forall t)$. For an arbitrary sequence of $\{q_{t+1}\}_{t=1}^{T}$, this condition need not hold. As such, update the world interest rate as

$$1 + q_t = \frac{\sum_{i=1}^{I}(r_{it-1}K_{it-1} + \Lambda_{it-1}^{w}L_{it-1})}{\sum_{i=1}^{I}(r_{it}K_{it} + \Lambda_{it}^{w}L_{it})} \text{ for } t = 2, \ldots, T. \tag{D.3}$$

The capital and the rental rate are computed in step (ii), while the wages are the values Λ^w above. The world interest rate in the initial period, q_1, has no influence on the model other than scaling the initial NFA position q_1A_{i1}; that is, it is purely nominal. We set $q_1 = \frac{1-\beta}{\beta}$ (the interest rate that prevails in a steady state) and choose A_{i1} so that q_1A_{i1} matches the desired initial NFA position in current prices.

Having updated the wages and the world interest rate, return to step (ii) and perform each step again. Iterate through this procedure until the excess demand is sufficiently close to zero. In the computations, we find that our preferred convergence metric,

$$\max_{t=1}^{T}\left\{\max_{i=1}^{I}\left\{\left|Z_{it}^{w}\left(\{\vec{w}_t, q_t\}_{t=1}^{T}\right)\right|\right\}\right\},$$

converges roughly monotonically toward zero. This provides the solution to a "sub-equilibrium" for an exogenously specified nominal investment rate.

(v) The last step of the algorithm is to update the nominal investment rate and terminal NFA condition. Until now, the Euler equation for investment in capital, condition 23, has not been used. We compute an "Euler equation residual" as

$$Z_{it}^{r}\left(\{\vec{\rho}_t\}_{t=1}^{T}\right) = \beta^{\sigma}\left(\frac{\frac{r_{it+1}}{P_{xit+1}} - \Phi_2(k_{it+2}, k_{it+1})}{\Phi_1(k_{it+1}, k_{it})}\right)^{\sigma}\left(\frac{P_{xit+1}/P_{cit+1}}{P_{xit}/P_{cit}}\right)^{\sigma} - \left(\frac{c_{it+1}}{c_{it}}\right). \tag{D.4}$$

Condition 23 requires that $Z_{it}^{r}\left(\{\vec{\rho}_t\}_{t=1}^{T}\right) = 0$ for all (i,t) in equilibrium. We update the nominal investment rates as

$$\Lambda_{it}^{r}\left(\{\vec{\rho}_t\}_{t=1}^{T}\right) = \rho_{it}\left(1 + \psi Z_{it}^{r}\left(\{\vec{\rho}_t\}_{t=1}^{T}\right)\right). \tag{D.5}$$

To update ρ_{iT}, we need to compute $\Phi_2(K_{iT+2}, K_{iT+1})$, which is simply its steady-state value, $\Phi_2^{\star} = \delta - \frac{1}{\lambda}$; this serves as a boundary condition for the path of capital stocks.

Given the updated sequence of nominal investment rates, return to step (i) and repeat. Continue iterating until $\max_{t=1}^{T}\left\{\max_{i=1}^{I}\left\{|Z_{it}^{r}\left(\{\vec{\rho}_t\}_{t=1}^{T}\right)|\right\}\right\}$ is sufficiently close to zero.

Since the steady state cannot be determined independently from the transition path, we need to update our guess for the terminal (steady state) NFA position $\mathcal{A}_{iT+1}$. In our first iteration, we do not know what its steady-state value is, so we set it equal to zero. Given the initial guess, the first iteration delivers a sequence of NFA positions that, by the turnpike theorem, will converge to its steady-state value at some time $t^{\star} < T$. After our first iteration, we take the NFA position at $t^{\star}$ and use it as the terminal condition for our second iteration. We choose $t^{\star}$ as the closest lower integer to $T \times \left(\frac{\text{iterations}}{1+\text{iterations}}\right)$. In our algorithm we use $T = 150$ so that in iteration 2, $t^{\star} = 100$. This way of updating the terminal NFA position ensures that the model settles down to its steady state before and through T.

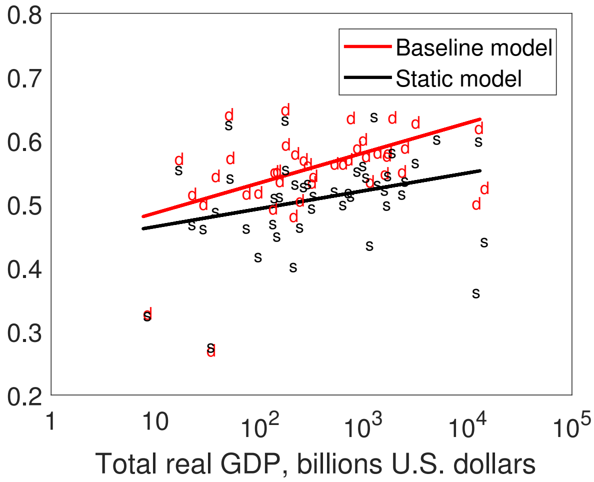
Our algorithm takes advantage of excess demand equations for our updating rules, just as in Alvarez and Lucas (2007). One advantage of using excess demand iteration is that we do not need to compute gradients to choose step directions or step size, as in the case of nonlinear solvers such as the ones used by Eaton, Kortum, Neiman, and Romalis (2016) and Kehoe, Ruhl, and Steinberg (2018). This saves computational time, particularly as the number of countries or the number of time periods is increased.

E The role of capital: A static model

We construct a static model that is essentially the one in Waugh (2010): Capital is an exogenous endowment in each country; there is no investment goods technology (no capital accumulation or adjustment costs); and trade is balanced. The tradable intermediates are used only in the production of final goods and other intermediates. The only difference relative to Waugh (2010) is that the value-added shares in final goods production and intermediate goods production are country specific.

Calibration In calibrating the static model, we need to take a position on how we map the static model to the data since capital stock in the model is fixed and does not depend on tradables. The intermediate goods sector is the same as in our baseline model: $\nu_{mi}^{s} = \nu_{mi}$, where the superscript "s" denotes the static value. We combine the consumption and investment goods sectors and interpret the combination as one final goods sector. That is, ν_{ci}^{s} is the ratio of the sum of value added of the consumption and investment goods to the sum of gross output of consumption and investment goods in country i. Figure E.1 illustrates ν_{ci} for the static model and for the baseline calibration in Section 3. The tradables intensity, $1 - \nu_c$, in consumption goods is higher in the static model relative to the baseline model for practically every country in our sample.

Figure E.1: Value-added share in consumption goods sector: ν_c



Notes: The letters s and d in each scatter plot denote the value-added share in the final goods sector in the static model and the value-added share in the consumption goods sector in the baseline dynamic model, respectively. Horizontal axis—Total real GDP data for 2014. The value of ν_c in the baseline model is the same as in Figure 1.

We then calibrate productivities and trade costs to match income per worker, the price of intermediates relative to consumption, and trade shares, as in Section 3. The trade costs are the same as in our baseline model since the structural equation used to calibrate the trade costs in the static model is also equation (5) and the data are the same. Finally, the initial capital stock is taken directly from the data, as in the baseline calibration.

Results We conduct a 20 percent unanticipated, uniform, and permanent trade liberalization in the static model. To compute the gains from trade in the static model, recall that the income per worker in the static model is given by

$$y_i \propto \underbrace{\left(\frac{A_{ci}}{B_{ci}}\right) \left(\frac{\left(\frac{T_{mi}}{\pi_{ii}}\right)^{\frac{1}{\theta}}}{B_{mi}}\right)^{\frac{1-\nu^s_{ci}}{\nu^s_{mi}}}}_{\text{TFP}} (k_i)^{\alpha}. \tag{E.1}$$

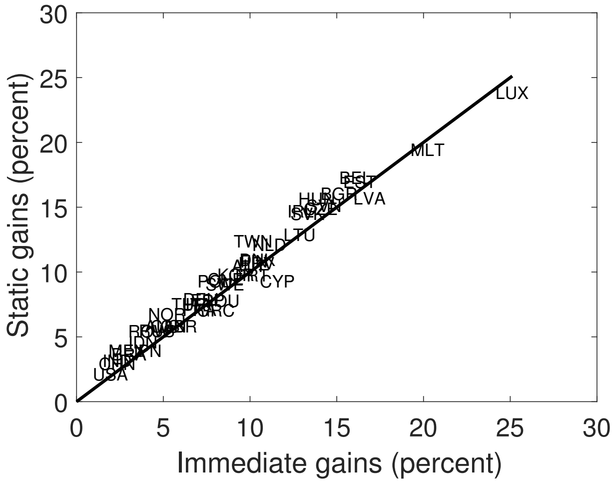
The static gain is computed according to

$$1 + \frac{\lambda_i^{static}}{100} = \frac{\hat{y}_i}{y_i^{\star}}, \tag{E.2}$$

where $\hat{y}_i$ is the income per worker in country i after the trade liberalization.

Figure E.2 illustrates the static gains according to (E.2) and the immediate gains according to (11) in Section 5.1. The two gains are practically identical.

Figure E.2: Immediate gains in the baseline model and gains in the static model



Notes: Gains following an unanticipated, uniform, and permanent 20 percent trade liberalization. Horizontal axis—Immediate change in income per worker along the transition path in the baseline dynamic model. Vertical axis—Gain in the static model. The solid line is the 45-degree line.

Despite the fact that (i) the static gains accrue immediately after the liberalization and there is no cost to increasing consumption, (ii) in the static world none of the tradables are allocated to inputs that increase future production, and (iii) the immediate gain in Section 5.1 used just a component of the transition path, the two gains look the same. Thus, Figure E.2 implies that the role of capital accumulation noted in Section 5.1 continues to hold.

F A two-country version of our baseline model

In this section, we calibrate a two-country version of our model in Section 2 and highlight the differences between the multicountry exercise and the two-country exercise. The theoretical channels for the gains in the two-country model are the same as those in the baseline model.

The differences arise in mapping the two models to the data and in the quantitative results.

Mapping the two-country model to the data To map the model to the data, one would pick a country of interest, say the United States, and then set the other country as ROW. To infer the parameters for ROW, one would then aggregate the data for all other countries. As is typically done in trade models, the trade costs are normalized so that there is no cost to ship goods within a country. That is, the trade cost is the *additional* cost of shipping across a pre-defined border. With the United States and ROW as the two countries, China and Mexico are both in ROW, and one would assume that there is no cost to trade between China and Mexico. So any trade distortions between China and Mexico would end up being attributed to lower productivity in ROW. This would affect the dynamic gains resulting from reductions in trade costs since, as we demonstrated in Section 4.2, the gains depend on the initial levels of trade costs and are nonlinear in the size of the reduction. The mapping from our baseline model to the data is more straightforward and does not suffer from such aggregation problems.

Counterfactual analyses If we are interested in the welfare gains of more than one country, we would have to change the country of interest one at a time in the two-country model. For instance, in the case of Portugal, ROW would now include the United States and we would have to assume there is no cost to trade between the United States and China. Thus, for each two-country model, we would have to construct a different version of ROW, essentially rendering the comparisons of gains across countries meaningless.

It is not clear how to conduct a counterfactual exercise of reducing only the policy-induced trade costs in a two-country model using gravity variables such as distance, language, a common border, etc., similar to what we did in our baseline model in Section 4.3. Furthermore, in a two-country model, we cannot study the welfare gains from multilateral trade reforms.

Quantitative implications In the two-country model, the dynamic gains are almost the same as the steady-state gains, but in the multicountry model the dynamic gains range from 63 percent to 92 percent of the steady-state gains. For instance, for the 20 percent reduction in trade costs in our baseline model, the dynamic gain is 21.9 percent for Bulgaria, but the steady-state gain is 24.6 percent. In the two-country model, the corresponding numbers are 14.6 percent and 14.8 percent. In the multicountry model, the price of investment relative to consumption declines by 7.2 percent after the liberalization, whereas in the two-country model the relative price declines by less than 5 percent. Thus, trade liberalization results in a higher rate of transformation of consumption into investment in the multicountry model than in the two-country model. Hence, Bulgaria ends up with higher capital, higher income, and higher consumption in the steady state in the multicountry model.

In both models, MPKs are equalized across countries via financial resource flows. In the two-country model of the United States and ROW, the United States runs a current account deficit after the trade liberalization but runs a surplus in the multicountry model. In the two-country model, the United States is smaller than ROW and resources flow from ROW to the United States in order to equalize the MPKs. In the multicountry model, however, while the size of the United States has not changed, it is large relative to several countries and resources flow from the United States to smaller countries such as Bulgaria and Portugal.

Some of these points can be addressed with a three-country model. However, there is no substantial computational advantage to solving a three-country model versus a 44-country model; it takes only 31 minutes on a standard 3.2 GHz Intel i5 iMac using our algorithm to solve the 44-country model. Furthermore, the three-country model suffers from the same aggregation issues described above.

G Multi-sector model with input-output linkages

We enrich our baseline model by incorporating a complete IO structure across four sectors. This builds on Caliendo and Parro (2015), where every sector's output goes into intermediate and final use. Different from their paper, the final use is split into consumption and investment, thereby introducing dynamics via capital accumulation. We also introduce one-period bonds to allow for endogenous trade imbalances and current accounts.

Countries are indexed by $(i, j) = 1, \ldots, I$, sectors by $(n, k) = 1, \ldots, N$, and time by $t = 1, \ldots, T$. There are four sectors: durable goods, non-durable goods, durable services, and non-durable services. In each sector, there is a continuum of varieties that are tradable. Trade in varieties is subject to iceberg costs. Each country has a representative household that owns the country's primary factors of production, capital, and labor. Capital and labor are mobile across sectors within a country but are immobile across countries. The household inelastically supplies capital and labor to domestic firms, and it purchases output from each sector and allocates it toward consumption and investment. Investment augments the stock of capital. Households can trade one-period bonds so that trade imbalances are endogenous. There is no uncertainty and households have perfect foresight.

Endowments The representative household in country i is endowed with workforce L_i. In each period, households supply labor inelastically. In period 1 the household in country i is endowed with an initial stock of capital, K_{i1}, and an initial NFA position, $\mathcal{A}_{i1}$.

Technology There is a unit interval of potentially tradable varieties in each sector indexed by $v^n \in [0,1]$, for $n = 1, \ldots, N$.

Within each sector, country i bundles all of the varieties with constant elasticity in order to construct a sectoral composite good according to

$$Q_{it}^n = \left[\int_0^1 Q_{it}^n (v^j)^{1-1/\eta} dv^n \right]^{\eta/(\eta-1)},$$

where η is the elasticity of substitution between any two varieties. The term $Q_{it}^n(v^n)$ is the quantity of variety v^n used by country i at time t, which can be either imported or purchased domestically, to construct the sector-n composite good. The composite good, Q_{it}^n, is allocated for domestic use as either an intermediate input or for final consumption or investment.

Each variety can be produced using capital, labor, and composite goods:

$$Y_{it}^n(v^n) = z_i^n(v^n) \left(A_i^n K_{it}^n(v^n)^{\alpha} L_{it}^n(v^n)^{1-\alpha} \right)^{\nu_i^n} \left(\prod_{k=1}^{N} M_{it}^{nk}(v^n)^{\mu_i^{nk}} \right)^{1-\nu_i^n}.$$

The term $M_{it}^{nk}(v^n)$ denotes the quantity of the composite good of type k used by country i to produce $Y_{it}^n(v^n)$ units of variety v^n in sector n at time t. $K_{it}^n(v^n)$ denotes the amount of capital stock used and $L_{it}^n(v^n)$ denotes the amount of workers employed.

The country-specific parameter $\nu_i^n \in [0,1]$ is the share of value added in total output in sector n, while $\mu_i^{nk} \in [0,1]$ is the share of composite good k in total spending on intermediates by producers in sector n, with $\sum_k \mu_i^{nk} = 1$. The term α denotes capital's share in value added.

The term A_i^n is the fundamental productivity in sector n of country i. The term $z_i^n(v^n)$ scales gross output of variety v^n in sector n of country i. Following Eaton and Kortum (2002), gross-output productivity in sector n for each variety is drawn independently from a Fréchet distribution with sector-specific shape parameter θ^n. The c.d.f. for the productivity draws in sector n is $F^n(z) = \exp(-z^{-\theta^n})$.

Preferences The representative household's preferences are given by

$$\mathcal{U}_i = \sum_{t=1}^{T} \beta^{t-1} \frac{\left(\frac{C_{it}}{L_i}\right)^{1-1/\sigma}}{1-1/\sigma}.$$

Consumption, C_{it}, bundles the composite goods from all sectors according to

$$C_{it} = \prod_{n=1}^{N} \left(C_{it}^{n}\right)^{\omega_i^{cn}},$$

where C_{it}^{n} denotes consumption of the sector-n composite good by country i at time t and ω_i^{cn} denotes sector n's weight in the country i's consumption bundle (i.e., $\sum_{n=1}^{N} \omega_i^{cn} = 1$).

Capital accumulation The representative household enters each period with K_{it} units of capital. A fraction δ depreciates during the period, while investment, denoted by X_{it}, adds to the stock of capital subject to an adjustment cost. The stock of capital is then carried over into the next period. Thus, with $K_{i1} > 0$ given, the capital accumulation technology is

$$K_{it+1} = (1-\delta)K_{it} + \delta^{1-\lambda} X_{it}^{\lambda} K_{it}^{1-\lambda}.$$

The term λ is the elasticity of capital accumulation with respect to investment. Investment in country i at time t, X_{it}, bundles the investment of composite goods from all sectors:

$$X_{it} = \prod_{n=1}^{N} \left(X_{it}^{n}\right)^{\omega_i^{xn}},$$

where X_{it}^{n} denotes investment of the sector-n composite good by country i at time t and ω_i^{xn} denotes sector n's weight in the country i's investment bundle (i.e., $\sum_{n=1}^{N} \omega_i^{xn} = 1$).

Net-foreign asset accumulation The representative household enters each period with an NFA position $\mathcal{A}_{it}$. If $\mathcal{A}_{it} > 0$, then country i has a positive balance at time t and a debt position otherwise. The NFA asset position is augmented by net purchases of bonds, B_{it}, the current account balance. Thus, the NFA position evolves according to

$$\mathcal{A}_{it+1} = \mathcal{A}_{it} + B_{it}.$$

Household constraints The household can borrow or lend to the ROW by trading one-period bonds, where B_{it} denotes the value of the net purchases of bonds. The world interest rate on one-period bonds at time t is denoted by q_t. Consumption and investment in each sector must be non-negative. The period budget constraint is given by

$$\sum_{n=1}^{N}(P_{it}^{n}C_{it}^{n}+P_{it}^{n}X_{it}^{n})+B_{it}=r_{it}K_{it}+w_{it}L_{i}+q_{t}\mathcal{A}_{it}.$$

Trade International trade is subject to barriers. Country i must purchase $d_{ij}^{n}\geq 1$ units of any variety of sector n from country j in order for one unit to arrive; $d_{ij}^{n}-1$ units *melt* away in transit. As a normalization, $d_{ii}^{n}=1$ for all (i,n).

Equilibrium A competitive equilibrium satisfies the following conditions: (i) Taking prices as given, the representative household in each country maximizes its lifetime utility subject to its budget constraint and technologies for accumulating physical capital and assets; (ii) taking prices as given, firms maximize profits subject to the available technologies; (iii) intermediate varieties are purchased from their lowest-cost provider subject to the trade costs; and (iv) markets clear. At each point in time, world GDP is defined as the numéraire: $\sum_i r_{it}K_{it}+w_{it}L_{it}=1$; i.e., all prices are expressed in units of current world GDP.

Calibration The calibration exercise is applied to 43 countries and ROW. Economic activity is split across four sectors of the economy: (1) durable goods; (2) durable services; (3) non-durable goods; and (4) non-durable services.

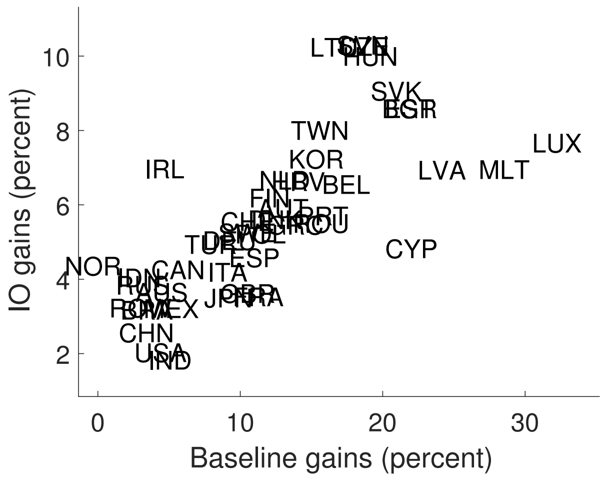
The primary data sources include version 9.0 of the PWT and the WIOD.

Our calibration uses data for 2014 and assumes that the world is in steady state in that year. This is the latest year for which both PWT and WIOD data are available.

We map sectors in our model to sectors in the data as follows. The non-durable goods sector corresponds to ISIC categories 01-28, durable goods sector corresponds to ISIC categories 29-35, durable services sector corresponds to ISIC 45, and non-durable services sector corresponds to the remaining ISIC categories.

Counterfactual We perform an unanticipated, uniform, permanent trade liberalization in which we reduce the trade costs of the durable and non-durable goods sectors by 20 percent, respectively. We compute dynamic welfare gains from trade and compare the results to those in our baseline model (see Figure G.1). We find that the two gains are highly correlated, but the gains tend to be lower in the IO model.

Figure G.1: Welfare gains from trade: IO model and baseline model



Notes: Results following an unanticipated, uniform, and permanent 20 percent trade liberalization. Horizontal axis—Baseline dynamic gains. Vertical axis—Gains in the IO model.

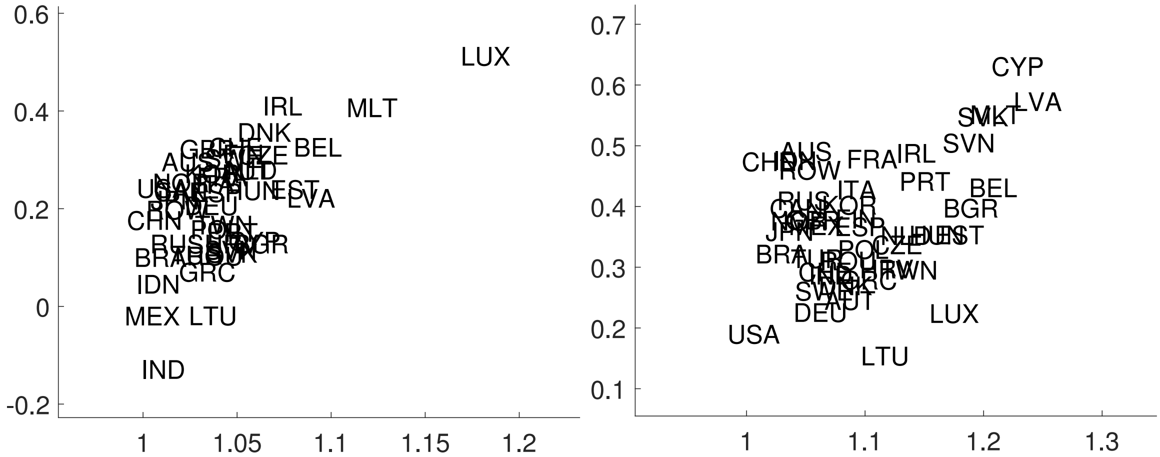
To understand why the gains are lower in the IO model, we compare changes in TFP and capital between steady states in the two models. Differences in the response of TFP are partly driven by the difference in the tradables intensity of the consumption basket between the two models. In the baseline model, the average tradables intensity of the consumption basket is $1 - \nu_c = 0.44$ and, in the IO model, it is $\omega^{c,DG} + \omega^{c,NG} = 0.23$ (DG and NG correspond to durable goods and non-durable goods). A larger tradables intensity in the baseline model contributes to a larger response of TFP. Figure G.2a shows that countries that have a larger difference in this tradables intensity between the two models also have a larger difference in the response of TFP.

Similarly, differences in the response of capital are partly driven by the difference in the tradables intensity in the investment basket between the two models. In the baseline model, the average tradables intensity of the investment basket is $1 - \nu_x = 0.67$ and, in the IO model, it is $\omega^{x,DG} + \omega^{x,NG} = 0.29$. Figure G.2b shows that countries that have a larger difference in this tradables intensity between the two models also have a larger difference in the response of capital.

Figure G.2: Change in TFP and capital versus difference in tradables intensity between the IO model and baseline model

(a) TFP

(b) Capital



Notes: Results following an unanticipated, uniform, and permanent 20 percent trade liberalization. Horizontal axis (a)—Difference in tradables intensity in consumption between the baseline and the IO model. Vertical axis (a)—Steady-state change in TFP in the baseline model relative to that in the IO model. Horizontal axis (b)—Difference in tradables intensity in investment between the baseline and the IO model. Vertical axis (b)—Steady-state change in the capital stock in the baseline model relative to that in the IO model.