Capital Flows in Global Value Chains

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PRELIMINARY†

Abstract

This paper develops a dynamic general equilibrium model that accounts for the use of capital services in global value chains. Whereas static models treat capital as a primary factor and investment as final use, I model the per-period services provided by invested capital as intermediate inputs in production. In my framework, a reduction in the price of investment goods lowers the rental prices (user costs) of capital deployed in downstream industries. Using data from the World Input-Output Database and the U.S. BEA, I find that accounting for capital services in global value chains more than doubles the per-period welfare impact of productivity shocks and trade liberalization.

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†Results are preliminary and subject to change. Comments are especially welcome.

1 Introduction

Global production is a complex process requiring not only intermediate inputs but also physical and intangible capital. A nascent literature on global value chains (see Antràs and Chor, 2021 for a summary) has modeled and quantified the complex input-output linkages formed through intermediate input use across industries and source countries. However, it has paid less attention to the services required of capital in production. Typical quantitative models of trade treat capital as a primary factor in fixed supply. These assumptions preclude a shock to the prices of capital goods from lowering the production costs of downstream industries that rely on the services of such capital assets.

For example, a semiconductor value chain might involve the U.S. providing R&D, Japan supplying capital equipment, and China supplying the chemicals for a production site in Taiwan (which supplies local labor). A reduction in trade costs between Japan and Taiwan would lower the investment prices of capital equipment. Over time, assuming a competitive market, the rental price (or user costs) of capital equipment would fall, as would the prices of semiconductors produced in Taiwan.

But national accounting conventions make it hard for quantitative models to capture such linkages across industries. Most expenditures on machinery, equipment, software, and R&D are capitalized rather than expensed. These capital services required in production show up as value-added in national input-output tables rather than as a flow rental payment to the industries that supplied the initial capital goods. Models that treat value-added by capital as payments to a fixed factor would miss these endogenous changes in prices. Moreover, feedback loops in production amplify the importance of such linkages. Semiconductors are themselves an input in other capital-producing industries such as automobiles, whose services are required in the production of yet other industries, *ad infinitum*.

In this paper I develop a theoretical framework that treats the rents paid to capital symmetrically with expenses on intermediate inputs. In doing so I overcome two challenges. The first is empirical. Unlike input expenses, capital rents are often borne by the user. We lack market value transactions that record the rents paid out by a producing industry to owners of a given capital asset type (i.e. a supplying industry). The second is theoretical. Any model with capital formation is inherently dynamic. Decisions to invest in new capital depends on future economic conditions, current capital stocks, depreciation rates, and households' inter-temporal preferences.

I develop a multi-industry, multi-country dynamic general equilibrium model where capital coefficients in production can be calibrated using detailed asset-by-industry investment data provided by the US Bureau of Economic Analysis (BEA). In the steady state, investment exactly replenishes the depreciation on existing capital. The levels of capital (of each asset type) are pinned down by the required rate of return under standard household intertemporal preferences. This relationship allows me to use BEA data on the flow of investments from a supplying industry to a using industry to infer the implied rental payments to capital of any given type in any using industry. In the same way that data on intermediate expenses can be used to calibrate intermediate input coefficients, I use the implied rental payments (or user costs) to calibrate capital service coefficients.

The steady state of the dynamic model admits a closed form solution. I show how standard "hat-algebra" machinery deployed in quantitative trade models (surveyed in Costinot and Rodríguez-Clare, 2014) can be used to solve for the exact change in welfare (per-period real consumption) across steady states in response to any permanent unanticipated shock. This allows me to compare outcomes in the steady-state of my dynamic model to a repeated equilibrium in conventional static models.

There are however two substantive differences between my dynamic model and conventional static models. First, the expanded matrix of input-output coefficients in the calibrated dynamic model reflects not only expenses on intermediate inputs but also rental payments to capital holders (or implicitly, user costs of capital). Global value chains in the dynamic model are thus potentially wider as well as deeper. Industries are more inter-linked than static models would assume. Second, final consumption by households (per-period welfare in my model) is financed out of both labor income as well as capital gains from investment. Such income effects change equilibrium market clearing conditions and thus potentially change the response of welfare to economic shocks.

I use the model to revisit the extent to which countries and industries are inter-linked in the global economy. In the absence of detailed investment-by-industry data from non-U.S. countries, I assume that the *relative* user costs of different capital services in a given producing industry are identical across countries. This allows me to apportion the total value-added by capital in any industry and any country into user costs from various supplying industries (and into source countries, using standard import proportionality assumptions). I assess the importance of these new value chains that are formed through recognizing capital's role as an intermediate, rather than primary, input in production.

Quantitatively, welfare gains from trade liberalization are more than double the gains in conventional calibrations that treat capital as a primary input and investment as final use. Recognizing capital as intermediate rather than primary inputs raises the overall intermediate share in the global economy, thereby amplifying the knock-on effects of price declines across industries. I also find that the increased gains manifest disproportionately among capital-intensive industries and countries. In other words, static-model calibrations are biased towards finding smaller price declines in capital-intensive industries because these industries are assumed to be more downstream (closer to final use).

The results in the paper do not depend on any specific calibration relating to the open economy. In my second quantitative exercise I focus on the US economy and study the impact of U.S. industry-level productivity shocks on domestic welfare. Once again, treating capital services as intermediate inputs more than doubles the welfare impact of productivity shocks relative to an alternative calibration where capital is treated as a primary input. The relative differences across models are larger for industries that supply a higher share of their output for investment rather than consumption. These capital-supplying industries are much more upstream in my model relative to previous calibrations.

Contributions in Relation to the Literature. This paper complements existing cross-sectional quantitative models that are calibrated using data from input-output tables, for example, to study production networks (Acemoglu et al., 2012; Carvalho and Tahbaz-Salehi, 2019) or the gains from trade (Costinot and Rodríguez-Clare, 2014). The calibrations in these models, however, do not attribute the use of capital services in production to supplying industries. Yet, given the focus of these models on long-run equilibrium changes in response to shocks, I argue that it is natural to think of capital as a dynamic input that is endogenous to economic shocks. This same argument is made by Hulten (1975) in the growth accounting literature. In a one-sector model of the domestic U.S. economy, he finds that the role of technical change in economic growth is doubled once he accounts for the induced effects of technical change on capital accumulation.

I enrich these existing quantitative results by augmenting input-output coefficients that reflect both intermediate input use as well as capital service flows between a pair of supplying and using industries. Recognizing the intermediate role of capital services in production magnifies the importance of global value chains and more than doubles the welfare impact of trade liberalization and productivity shocks. Despite relying on a dynamic model to provide theory-consistent calibrations, the framework I develop comes at no additional cost in computational complexity. The same machinery used to solve for changes in equilibrium outcomes in static models can be used to solve for changes in the per-period steady state in my dynamic model. The augmented input-output matrix also alters conventional measures of industry centrality and upstreamness, creating impetus for revisiting other empirical results in the literature on global value chains, such as optimal policy (Blanchard et al., 2021) or contracting (Antràs and Chor, 2013).

There are, of course, many existing papers that study trade in capital goods, but few that integrate trade in capital with trade in intermediates in a multi-country, multi-industry, quantitative setting.[1] In their handbook chapter, Costinot and Rodríguez-Clare (2014) perform a back-of-the-envelope calculation into how much the gains from trade would increase if capital value-added were re-assigned in proportion to an industry's use of intermediate inputs. The differences in their setting are much smaller than what I find. One plausible explanation is that their reassignment increases the depth of global value chains (strengthens existing linkages) but does not increase the breadth because industries that supply capital goods are still assumed to be suppliers of final consumption (investment).

My paper also relates to a literature on multi-sector real business cycle models (Long and Plosser, 1983; Horvath, 2000; Atalay, 2017; vom Lehn and Winberry, 2021). These dynamic models give fair treatment to investment and sector-specific capital formation, but focus mostly on short-run economic fluctuations and sectoral co-movement over the business cycle rather than long-run responses to shocks. Instead, I provide closed-form equations that solve for the long-run steady state of the economy as a function of the augmented input-output coefficients. I show that the "Leontief inverse" of the augmented input-output matrix can be used to assess the impact of industry-specific productivity shocks on per-period welfare. These results extend the celebrated Hulten (1978)'s theorem to include capital accumulation with a focus on comparative statics *across* steady states.

Finally, my paper provides a conceptual framework for reallocating capital value-added in production to their source—the industries (and countries) that supplied the capital assets that were in some prior period purchased as investment. This is related to recent research in macroeconomics studying the decline of labor shares in value-added.

[1] To name a few examples in this vein of research, Eaton and Kortum (2001) focus on equipment and Keller and Yeaple (2013) and Ramondo (2014) study knowledge capital. An exception is Eaton et al. (2016), who build a four-sector multi-country dynamic general equilibrium model to quantify the relative importance of shocks during the Great Recession. However, they use a different methodology to back out the share of production attributable to durables and structures (their two capital sectors), and in their setting services are non-traded and non-capitalized, so that the contribution of intellectual property products such as R&D in global value chains stands to be underestimated. Their focus is also on short-run dynamics, as per the RBC literature, rather than long-run steady-states.

Koh et al. (2020) argue that these macro trends can be completely attributed to changes in accounting conventions that has led to the capitalization of software and intellectual property products (IPP). Before a series of revisions to the system of national accounts, expenditures on software and IPP were expensed and treated as intermediate inputs. After the accounting rules were changed, the services performed by these inputs are registered as industry (capital) value added, thereby lowering labor's share of value-added. Barro (2021) makes a related argument that investment is double-counted in GDP: once when capital goods are purchased and again when rental returns on the investment are realized over future periods (as value-added). Given its symmetric treatment of expensed intermediate inputs and capital services, my framework is consistent with these arguments. The predictions from my model are robust and invariant across changes in accounting conventions.

Structure of the Paper. Section 2 illustrates how input-output tables record less information in settings where inputs are capitalized versus expensed, despite what should be a theoretical equivalence across the two concepts. Section 3 develops the theoretical framework. Section 4 details the data, model calibration, and quantitative results. Section 5 concludes.

2 Accounting for Intermediate Inputs and Capital

Using a stylized example, I show how the capitalization of expenditures in the national accounts have the potential to obfuscate our understanding of economic linkages across industries. I then explain how these accounting conventions materialize in real-world data. I illustrate how changes in the System of National Accounts' guidelines for intellectual property products have led to sharp temporal discontinuities in input-output tables published by the World Input-Output Database and the BEA.

2.1 A Stylized Example

Consider a stylized neoclassical economy populated by L workers who supply their labor inelastically and consume fish each period. Workers are infinitely lived and infinitely patient, so the real interest rate is zero. There are two industries in the economy: fishing rods and fish. Fishing rods are used to catch fish, and are thus intermediate inputs in the production of fish. Let the wage of a worker be the numeraire.

Table 1: Input-Output Table of Economy (A): Fishing Rods as Intermediate Goods

	Rods	Fish	Consumption	Investment	Output
Rods	0	$\frac{1}{2}L$	0	0	$\frac{1}{2}L$
Fish	0	0	L	0	L
Labor	$\frac{1}{2}L$	$\frac{1}{2}L$			
Capital	0	0			
Output	$\frac{1}{2}L$	L			

Consider two versions of this economy that feature the same production technology for fish but slightly different fishing rods. In version (A), fishing rods break after one year of use, so they are treated as an intermediate input per national accounting rules. It takes one worker to make a fishing rod (e.g. from bamboo, which is a free resource in infinite supply), and it takes one worker with one rod to catch one fish. Table 1 represents the input-output table of the equilibrium in this economy (labeled A). Rods are valued at one dollar a piece, and $\frac{1}{2}L$ rods are in use each period to catch fish.

In version (B), rods are twice as durable (so they last two years instead of one) but require two workers to produce.[2] Twice-durable fishing rods would however be treated as capital goods. In steady state, the input-output table of this economy now looks like Table 2. Each period, the same number of rods ($\frac{1}{2}L$) are in use to catch fish, but the contribution of fishing rods in production shows up as capital value added (user cost of capital). Half of these rods ($\frac{1}{4}L$) reach the two-year vintage mark and break, and are replaced by an equal investment of ($\frac{1}{4}L$) new rods. Since two workers are required to make this twice-durable rod, prices of fishing rods are two dollars instead of one, and the wage bill in the rod-making industry remains the same as version (A). In fact, the only difference across the two input-output tables is that the $\frac{1}{2}L$ of intermediate goods flow in version (A) appears twice in version (B): once as investment and then again as capital value added.

The two versions of the economy are in principle identical. Both versions feature the same number of workers in each sector, the same number of fishing rods in use, the same amount of fish consumed per period, and thus the same household welfare. However, whether fishing rods are treated as an intermediate or a capital good affects statistics as reported in the national accounts and data as recorded in the input-output table. GDP

[2] We know this technology is freely available because we can define the new fishing rod as a bundle of two rods where the second rod is automatically used after the first breaks.

Table 2: Input-Output Table of Economy (B): Fishing Rods as Capital Goods

	Rods	Fish	Consumption	Investment	Output
Rods	0	0	0	$\frac{1}{2}L$	$\frac{1}{2}L$
Fish	0	0	L	0	L
Labor	$\frac{1}{2}L$	$\frac{1}{2}L$			
Capital	0	$\frac{1}{2}L$			
Output	$\frac{1}{2}L$	L			

in version (A) is only L but GDP in version (B) is 50% higher, at $\frac{3}{2}L$. This illustrates how investment is double-counted if GDP numbers were to be used as a reference for consumption welfare (Barro, 2021). The full value of a fishing rod is counted once when it enters GDP as investment, and then again over the next two years in terms of capital value-added.

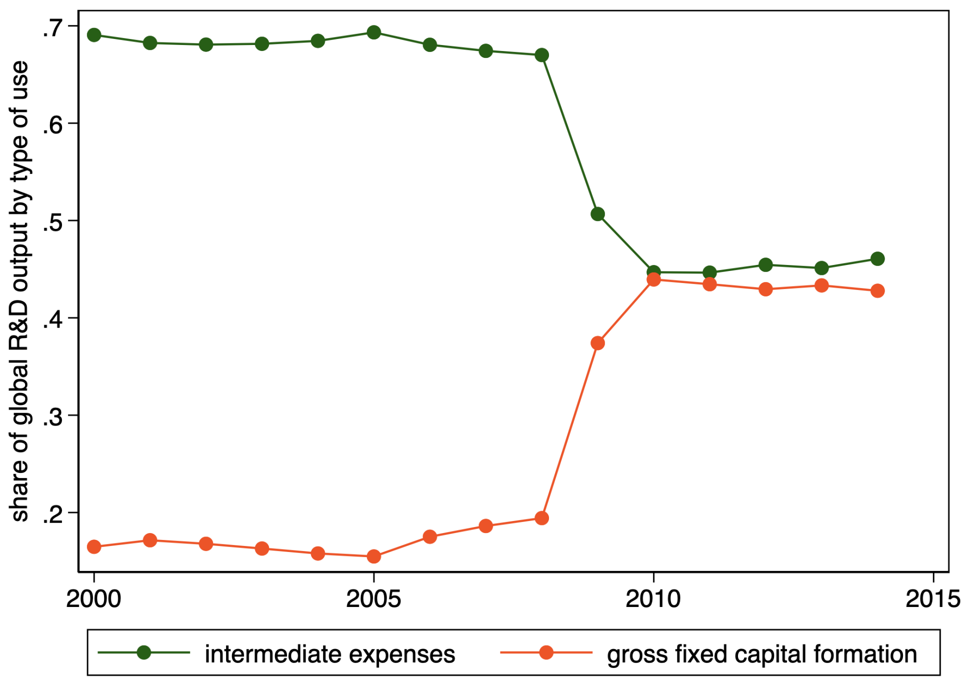
Capitalization in the national accounts also obscures our ability to measure economic interdependence across industries. In version (A) of the economy, the cost share of fishing rods in the production of fish is $\frac{1}{2}$. A productivity shock in the rods industry would lower the prices of fish by one half and would be accurately reflected by this cost share. However, in a naive calibration of an input-output model to version (B), simply because purchases of fishing rods are capitalized, a productivity shock in rods does not lower the price of consumed fish at all. Even if the invested value of fishing rods were appropriately accounted for as final use (from being a part of GDP), the effect of the productivity shock would lower the final price index by only one-third (its share in final use) rather than by one-half (the correct amount).

2.2 Changes in the System of National Accounts Guidelines

The above example illustrates how hard it is to trace and attribute the flow of capital in any cross-section. Capitalized expenditures in any producing industry that 'uses' capital show up only as value-added, without attribution to the supplying industry.

Another issue occurs in the time-series. Over the past two decades, changes in capitalization guidelines provided by the System of National Accounts have systematically reallocated bilateral industry flows away from intermediate expenses and towards investment (gross fixed capital formation). The most notable of these changes has been the

Figure 1: Capitalization of R&D since 2008: A View from the WIOD



Notes: Source: WIOD data, Nov 2016 version. The R&D sector is coded as M72 in the WIOD tables, "Scientific Research and Development". The share not shown is the share of output used for final consumption (use by households and governments). Computations are derived from data on the top 32 countries in the WIOD.

capitalization of software since 1993 as well as R&D and artistic originals since 2008.[3]

Figure 1 illustrates this accounting-induced reallocation from input-output flows to capital flows in the World Input Output Database (See Appendix A for more details on the data). Between 2008 and 2010, the share of R&D used for gross fixed capital formation more than doubled from 20% to 45%, with a corresponding decrease in the share of R&D output used as intermediate input expenses. An analyst treating capital as final use is thus likely to compute very different welfare impacts of a productivity shock in the R&D sector depending on whether they calibrate their model to data from 2007 or 2010.

I offer one more piece of evidence that capital goods play as active a role as intermediate inputs in global value chains. Appendix Figure C.1 plots the import share of expenditures by different end uses: (i) intermediate inputs, (ii) capital formation, and (iii) final use (by households and governments). Roughly 14% of intermediate inputs and capital formation expenditures are traded, and the two series track each other closely. On the other hand,

[3]See Koh et al. (2020) for more details and corresponding information on the BEA's treatment of software, R&D, and artistic originals. Corrado et al. (2009) argue that intangibles should be capitalized and that doing so would increase estimates of GDP, for the same reasons illustrated in the previous stylized example.

only around 8% of final use expenditures are imported. The fact that capital goods are just as imported as intermediate inputs suggests that—all else equal—trade liberalization would be predicted to have as large an impact on reducing prices of intermediate input-consuming industries as it would capital-intensive industries.

3 Theoretical Framework

I develop a theoretical framework where production requires intermediate inputs and one primary input, labor. Intermediate inputs consist of intermediate goods (and business services) that are consumed entirely within an accounting period, as well as the services of different capital assets deployed in the industry. This framework treats the purchase of an input that is exhausted in production symmetrically as the rental of a capital asset for its services rendered. My framework is thus robust to the potential differences in national accounting conventions across countries and over time illustrated in Section 2.

I use my dynamic framework to quantify the role of capital services in propagating shocks along production networks. To rationalize capital formation, I introduce the bare minimum assumptions required on the dynamic behavior of households. I develop the model in a closed-economy setting before introducing the open-economy extension.

In all the derivations below I focus on characterizing steady state outcomes instead of transition dynamics to the steady state. This focus on the long-run steady state allows me to compare the impact of economic shocks in my model to the impact on a repeated per-period equilibrium in a static model (which, of course, also does not feature any transition dynamics).

3.1 Closed Economy

Let $j, k = 1, ..., K$ denote the set of industries in the economy. Each supplying industry k's output can be used as (i) intermediate inputs in a producing industry j, (ii) capital formation (investment) in a producing industry j, and (iii) final consumption by households. The representative household in the economy has standard inter-temporal preferences

$$U = \sum_{t=0}^{\infty} \beta^t u(C_t),$$

where $\beta < 1$ is a discount factor, $u(.)$ is a concave function and the final good, C_t, is a Cobb-Douglas bundle of output for final consumption in each industry:

$$C_t = \prod_j C_{tj}^{\alpha_j},$$

with final consumption shares $\sum_j \alpha_j = 1$.

To keep the framework simple, there is no exogenous technological change and no economic uncertainty. Households have access to a savings technology in units of the final good. In steady state $C_t = C_{t-1}$ and the standard household Euler condition yields

$$1 + r^f = \frac{1}{\beta}, \tag{1}$$

where r^f is the interest rate on a one-period bond (in zero net supply) denominated in units of the final good. This rate of return is a useful benchmark for pricing households' (indirectly, firms') decisions to purchase investment assets of any type k, where k represents the supplying industry whose output is purchased for capital formation (e.g. the computer industry supplies computers as capital goods for other using industries). In equilibrium, given the assumed lack of risk in the model, rates of return are equalized across all investment opportunities.

I make the following assumptions on the production function and capital accumulation.

Assumption 1 (Production Function) *Output q_j in each industry j is given by a Cobb-Douglas function over labor inputs l, intermediate inputs m_k, and the services of deployed capital assets κ_k:*

$$q_j = A_j \cdot l^{\beta_j^L} \prod_{k=1}^{J} m_k^{\beta_{jk}^M} \prod_{k=1}^{J} \kappa_k^{\beta_{jk}^K}, \qquad \forall j = 1, ..., J. \tag{2}$$

where A_j is a Hicks-neutral productivity shifter, β_j^L is a labor coefficient corresponding to the labor share of output, β_{jk}^M are conventional input-output coefficients corresponding to the expenditures on input k by industry j as a share of output, and β_{jk}^K are capital service coefficients corresponding to the rental expenses (or implicit user costs) on capital asset k deployed in industry j as a share of output. The production function is constant returns to scale, satisfying

$$\beta_j^L + \sum_{k=1}^{J} \left(\beta_{jk}^M + \beta_{jk}^K\right) = 1, \qquad \forall j.$$

Assumption 2 (Capital Accumulation) *The capital stock deployed in industry j formed from output of industry k in the economy, $K_{jk,t}$, evolves over time given depreciation rate δ_k and new investment $I_{jk,t}$*

$$K_{jk,t+1} = (1 - \delta_k)K_{jk,t} + I_{jk,t} \qquad \forall k, \forall j. \tag{3}$$

Given these assumptions, the following equations describe the steady state of the dynamic model.

Definition 1 (Closed Economy Steady State) *Given a population size L, consumption coefficients $\{\alpha_j\}$, interest rate r^f, and production coefficients $\{\beta_{jk}\}$, the steady state of the closed economy features levels of capital $\{K_{jk}\}$ and output $\{X_j\}$ (in value-terms), a set of output prices per industry $\{P_j\}$ dual to the industry production functions in equation (2) and rental rates (user costs) per asset type $\{r_k\}$, relative to a numeraire wage, such that*

1. *The labor market clears:*
$$L = \sum_k \beta_k^L X_k,$$

2. *Markets for capital services clear for each asset type k in each producing industry j:*
$$r_k K_{jk} = \beta_{jk}^K X_j \qquad \forall k, \forall j,$$

3. *Investment in each producing industry j exactly replaces depreciated capital for each asset type k:*
$$I_{jk} = \delta_k K_{jk} \qquad \forall k, \forall j,$$

4. *The value of investment (newly deployed capital) equals a fraction $\frac{\delta_k}{r^f+\delta_k}$ of per-period rental payments (user costs) for each type of capital k in each producing industry j:*
$$P_k I_{jk} = \frac{\delta_k}{r^f + \delta_k} r_k K_{jk} \qquad \forall k, \forall j, \tag{4}$$

5. *Output markets clear in each industry: total supply in industry j equals, respectively, total demand for j as intermediate inputs, as investment (new capital formation), and as final household consumption (coming out of labor income and capital gains):*
$$X_j = \sum_k \left(\beta_{kj}^M + \frac{\delta_j}{r^f + \delta_j}\beta_{kj}^K\right) X_k + \alpha_j \left(L + \sum_k \sum_{j'} \frac{r^f}{r^f + \delta_{j'}}\beta_{kj'}^K X_k\right). \tag{5}$$

Equation (4) provides a link between the value of investment (purchases of new capital goods) with the rental payments to (user costs of) capital services provided by that asset type. This condition is the cornerstone of the calibration strategy in the next section. To derive this condition I use the fact that the household must be indifferent between investing in one-period bonds denominated in units of the final good (at interest rate r^f) and investing in capital goods from any supplying industry k. In other words, no arbitrage opportunities exist. In this neoclassical framework, assuming that households make capital investments and then rent capital to producers is equivalent to assuming that firms make capital investments by borrowing from households at a rate of return. In the exposition that follows, I take the point of view of a household considering the decision to invest in capital assets.

Let V_{jkt} denote the net present asset value of a unit of capital good k deployed in industry j at the start of a period t. This is equal to the rental rate of capital r_{jk} plus its value next period net of depreciation δ_k:

$$V_{jkt} = r_{jkt} + \frac{1}{1 + r_t^f}(1 - \delta_k)V_{jk,t+1}.$$

In steady state, asset values and rental rates are constant, so that

$$V_{jk} = \frac{r_{jk}}{1 - \frac{1}{1+r_t^f}(1 - \delta_k)}.$$

By no arbitrage, the interest rate on a one-period bond equals the return on investing in any capital asset k, so that

$$\frac{V_{jk}}{P_k} = 1 + r^f = \frac{r_{jk}}{P_k(1 - \frac{1}{1+r^f}(1 - \delta_k))},$$

which can be rearranged to yield an equation linking rental rates of capital to the prices of capital goods (for investment), where another interpretation of r_{jk} is Jorgenson (1963)'s user cost of capital:

$$P_k = \frac{1}{r^f + \delta_k} r_{jk} \qquad \forall j, k. \tag{6}$$

Therefore, in steady state, rental rates (or implicit user costs) of capital services, r_{jk}, move one-for-one with the price P_k of the underlying capital asset (output purchased for investment), and does not depend on the industry of deployment j.[4] In the rest of the paper (and in Definition 1) I have made use of this result and write rental rates r_k without reference to the using industry j.

In steady state, capital levels are constant for any given asset type k, so investment is just enough to cover depreciation, $I_{jk} = \delta_k K_{jk}$. Multiplying both sides of this condition into equation (6), the purchases of new capital goods from industry k for deployment in industry j can be related to the rental flows on capital, thus delivering equation (4).

Equation (4) reveals that investment $P_k I_{jk}$ will be weakly lower than the value-added by capital $r_k K_{jk}$. A fraction of value-added, $\frac{r^f}{r^f+\delta_k}$, is used instead to finance final consumption (along with labor income). This fraction serves to compensate households for delaying consumption to invest. In the limit as households are infinitely patient, as in our fishing example, compensation is no longer required. The value of investment in each period exactly equals the value-added by capital. As the required rate of return goes higher, levels of capital in equilibrium are depressed until the required rate of return is reached.

Comparison with multi-sector RBC models. The supply-side assumptions in my model differ slightly from those in standard multi-sector RBC models à la Long and Plosser (1983). In my model, production in a given industry j (equation 2) requires capital services of assets purchased from *each* supplying industry k. Capital assets depreciate at rate δ_k specific to the supplying industry (k) from which they are purchased. On the other hand, standard RBC models treat the combination of capital assets deployed in an industry as a composite that depreciates at a rate δ_j according to the using industry j.

Therefore, the dynamic equation for capital in my model (equation 3) is specific to each *supplying* asset k, whereas the dynamic equation for capital in RBC models is specific to each using industry (denoted j). In RBC models, investment I_j in industry j would be formed from a Cobb-Douglas bundle of supplying assets Q_{jk}, with coefficients given by, say, γ_{jk}. The two modeling assumptions are isomorphic only if the interest rate r^f is 0, or if all assets depreciate at the same rate $\delta_k = \delta,\ \forall k$. Under these edge cases, β^K_{jk} in my model equals $\gamma_{jk}\beta^K_j$ in standard RBC models, where β^K_j is the Cobb-Douglas coefficient on the capital composite in industry j's production function.

Outside of these edge cases, the two models would require different capital coefficients

[4] Clearly, this result relies on the assumption that assets of a given type k depreciate at the same rate δ_k regardless of industry of deployment j. It is trivial to extend the model to allow for depreciation rates (or other costs) that differ across j for a given type of capital asset k, though the data requirements would be heftier.

Table 3: Illustration of Economy (B) in terms of the Model's Input-Output Coefficients

	Rods	Fish	Consumption	Investment	Output
Rods	0	0	0	$\frac{\delta}{r^f+\delta}\beta^K X$	$\frac{\delta}{r^f+\delta}\beta^K X$
Fish	0	0	X	0	X
Labor	$\frac{\delta}{r^f+\delta}\beta^K X$	$\beta^L X$			
Capital	0	$\beta^K X$			
Output	$\frac{\delta}{r^f+\delta}\beta^K X$	X			

to rationalize the same data. When investors require a rate of return above zero, assets that have low depreciation rates are characterized by lower levels of investment $P_k I_k$ in equilibrium (see equation 4) relative to their true share of costs in production $r_k K_k$. Intuitively, a lower level of depreciation gives an asset a longer service life, meaning that investors do not realize their investment returns until on average much later. The more than investors are impatient, the higher are equilibrium rental prices required, and the lower is investment in steady state.

For example, compare real estate with software, both capital goods in use in virtually every industry. Suppose that the share of capital value added in each using industry is split equally between capital services provided by the two assets. But given its lower depreciation rate, real estate will attract lower investment in equilibrium than software so that the return per unit of real estate invested earns a premium to compensate for households' impatience.

An Input-Output Representation of the Model. Given the Cobb-Douglas structure of the economy, data from input-output tables can be easily mapped to the model's coefficients. As an example, consider the stylized two-industry fishing economy (B) from Section 2. Suppose that there are no intermediate goods, the production of rods requires only labor, and the production of fish requires labor plus the services of rods with coefficients β^L and $\beta^K = (1 - \beta^L)$. Let the value of fish equal X. Table 3 illustrates the input-output table of this general two-industry fishing economy and how all other entries in the input-output table can be computed as a function of X.

To close out for the general equilibrium of the model, we can solve for X in terms of L, the exogenous household size, using labor market clearing

$$
\begin{aligned}
L &= \frac{\delta}{r^f + \delta}\beta^K X + \beta^L X \\
\implies X &= L\left(\frac{\delta}{r^f + \delta}\beta^K + \beta^L\right)^{-1} .
\end{aligned}
$$

The last line implies that total final consumption in the economy each period can be decomposed into labor income and capital gains:

$$
X = \underbrace{L}_{\text{labor income}} + \underbrace{\frac{r^f \beta^K}{r^f \beta^L + \delta} L}_{\text{capital gains}} .
$$

It is worth noting that capital gains lies in between value-added by capital ($\beta^K X$) and zero, and depends on production shares, the risk-free rate, and the depreciation rate. Taking the limit as $r^f \to 0$, households no longer demand a reward for patience, so there are no capital gains in steady state. Finally, when $\beta^L = \beta^K = 0.5$ we recover the specific entries in the example behind Table 2. The rest of the paper generalizes this setting to multiple industries and then multiple countries.

3.2 The Impact of Productivity Shocks on Welfare

Proposition 1 derives the impact of industry productivity shocks ($\mathrm{d}\log A_j$) on per-period welfare in the steady state of the economy (under definition 1). I focus on comparative statics across steady states rather than transition dynamics. I assume that productivity shocks are permanent and unanticipated. I measure and define welfare as real per-period consumption, C, to facilitate comparison with existing static models.

Proposition 1 (Productivity Shocks in Autarky) *Under autarky, the impact of unanticipated and permanent productivity shocks ($\mathrm{d}\log A_j$) on steady-state per-period welfare in the economy is given by*

$$
\mathrm{d}\log C = \boldsymbol{\alpha}'(\boldsymbol{I} - \boldsymbol{B})^{-1}\,\mathrm{d}\log \boldsymbol{A}, \tag{7}
$$

where final consumption C denotes household per-period welfare, $\boldsymbol{\alpha}$ is an industry-vector of final spending shares, $\boldsymbol{I}$ is the identity matrix, and $\boldsymbol{B}$ is a $K \times K$ extended input-output matrix with *coefficients $\boldsymbol{B}_{jk}$ given by intermediate input and capital service cost shares:*

$$\boldsymbol{B}_{jk} = \beta_{jk}^{M} + \beta_{jk}^{K}.$$

The term $\boldsymbol{\alpha}'(\boldsymbol{I} - \boldsymbol{B})^{-1}$ is a $1 \times K$ vector of industry-importance weights from the point of view of welfare, incorporating both demand-side preferences ($\boldsymbol{\alpha}$) and production-side coefficients on intermediate inputs (β_{jk}^{M}) and capital services (β_{jk}^{K}).

Incidentally, in this setting where capital services are consumed in production, Hulten (1978)'s theorem no longer holds. For most plausible configurations of the economy, Domar weights (industry output to GDP ratios) are no longer sufficient statistics for assessing the impact of productivity shocks on welfare. The following corollary makes this point clear; it shows how the vector of Domar weights differ from the welfare-relevant vector $\boldsymbol{\alpha}'(\boldsymbol{I} - \boldsymbol{B})^{-1}$ from Proposition 1.

Corollary 1 (Domar Weights) *The $1 \times K$ vector of Domar weights, defined as industry output relative to GDP, is given by:*

$$\frac{\boldsymbol{X}'}{GDP} = \left(\frac{L}{L + \sum_j \left(\sum_k \beta_{jk}^{K} \right) X_j} \right) \boldsymbol{\alpha}'(\boldsymbol{I} - \boldsymbol{\Upsilon})^{-1},$$

where $\boldsymbol{\Upsilon}$ is a modified 'Leontief'-style matrix with elements $\boldsymbol{\Upsilon}_{jk}$ given by

$$\boldsymbol{\Upsilon}_{jk} = \beta_{jk}^{M} + \frac{\delta_k}{r^f + \delta_k} \beta_{jk}^{K} + \alpha_k \left(\sum_{k'} \frac{r^f}{r^f + \delta_{k'}} \beta_{jk'}^{K} \right).$$

There are three reasons why Domar weights are no longer informative. The most obvious is that Proposition 1 compares differences across steady states of the model before and after a shock, whereas Hulten (1978) focuses on local changes in a model with intermediate inputs (implicitly, holding capital fixed). The second reason is that my model focuses on per-period real consumption C in steady state, whereas Hulten focuses on GDP, which (by definition) includes both labor income and value-added by capital. This explains the adjustment by a factor of $\frac{L}{GDP}$ in the Domar weight. Finally, industry output in my model depends on demand for investment and final demand generated from capital gains. This causes centrality measures derived from inverting industry output, $(\boldsymbol{I} - \boldsymbol{\Upsilon})^{-1}$ to be distorted relative to a Leontief inverse based on true production coefficients, $(\boldsymbol{I} - \boldsymbol{B})^{-1}$.

In the special case where $r^f = 0$, all of capital value-added is re-invested. Since investment is counted as industry output, Domar weights contain the right information for the "input centrality" of each industry. The two measures of centrality coincide: $\boldsymbol{\Upsilon} = \boldsymbol{B}$. Domar weights as observed in the data (multiplied by $\frac{GDP}{L}$) act as sufficient statistics for computing the impact of productivity shocks on welfare. Moreover, if capital plays no role in production ($\beta^K_{jk} = 0$) Hulten's result emerges as a special case of Proposition 1.

Intuition. Proposition 1 also reveals a simple intuition for why capital services amplify the impact of industry-level shocks in the economy. When capital services are modeled analogously to intermediate inputs in production, the extent of "roundabout production" increases. This result does not depend on the number of industries in the economy. Take, for example, a one-sector economy (so $\alpha = 1$). Equation (7) simplifies to

$$\mathrm{d}\log C = \frac{1}{1-B}\,\mathrm{d}\log A,$$

where B is the combined intermediate input and capital service share in production. For conventional values of cost-shares in production—intermediate inputs at 50%, labor at 25%, and capital services at 25%, going from pure value-added to intermediate inputs doubles the impact of productivity shocks (B increases from 0 to 0.5), and going from a model with intermediate inputs to both intermediate inputs and capital services further doubles the impact of productivity shocks (B increases from 0.5 to 0.75).

3.3 Open Economy

I now extend the simple framework introduced above to an open-economy setting. Let $n, i = 1, \ldots, N$ denote the set of countries. Each country produces a differentiated variety of an industry good j. Differentiated varieties are combined to form an industry composite good with CES elasticity of substitution $\theta_j + 1$. This same composite is purchased as intermediate inputs, investment, and final consumption.

To keep the focus on trade in goods and services, I assume that each country operates under financial autarky. All purchases of capital goods from abroad are financed and owned by the local economy (the importer).[5] I model trade deficits as exogenous transfers

[5]In equilibrium, capital goods will be traded but never capital services, provided that shipping a 'unit' of capital services bears the same trade cost as shipping a unit of that capital good itself. In other words, an American household would not buy a U.S. computer and ship it to a producer in China for rent for one period and then have it shipped back at the end of the rental period. The round-trip shipping costs of such 'trade' in capital services makes the rental cost higher than if Chinese households bought the same U.S. computer (an import of the capital *good*), paid for the shipping once, and rented it out to Chinese producers

of wealth across countries.

Assumption 3 *Each country operates under financial autarky. There is no FDI.*

Definition 2 (Open Economy Steady State) *Given population size L_i, consumption coefficients α_i, interest rate r_i^f, production coefficients β_i and exogenous trade imbalances D_i in each country i, and bilateral iceberg trade costs τ_{nij} and trade elasticities θ_j in each industry j, the steady state of the open economy is described levels of capital $\{K_{ij}\}$ and output $\{X_{ij}\}$ (in value-terms), a set of output prices per industry $\{P_j\}$, rental rates per asset type $\{r_j\}$, and relative wages per country $\{w_i\}$, such that*

1. *The labor market clears in each country i*

$$w_i L_i = \sum_k \beta_{ik}^L X_{ik}, \qquad \forall i,$$

2. *Markets for capital services clear for each asset type k in each deployed industry j in each country i:*

$$r_{ik} K_{ijk} = \beta_{ijk}^K X_{ij} \qquad \forall i, k, j,$$

3. *Investment in each type of capital asset k by industry of deployment j achieves the required rate of return*

$$P_{ik} I_{ijk} = \frac{\delta_{ik}}{r_i^f + \delta_{ik}} r_{ik} K_{ijk} \qquad \forall i, k, j, \tag{8}$$

4. *Output markets clear in each industry j in each country i:*

$$X_{ij} = \sum_n \pi_{nij} \left[\sum_k \left(\beta_{nkj}^M + \frac{\delta_{nj}}{r_n^f + \delta_{nj}} \beta_{nkj}^K \right) X_{nk} + \alpha_{nj} \left(w_n L_n + D_n + \sum_j \sum_k \frac{r_n^f}{r_n^f + \delta_{nj}} \beta_{nkj}^K X_{nk} \right) \right], \tag{9}$$

5. *Import shares take the constant-elasticity form:*

$$\pi_{nij} = \frac{(\tau_{nij} c_{ij})^{-\theta_j}}{\sum_{i'} (\tau_{ni'j} c_{i'j})^{-\theta_j}},$$

every period thereafter.

6. *Unit costs of production in each country i in industry j take the Cobb-Douglas form:*

$$c_{ij} = A_{ij}^{-1} w_i^{\beta_{ij}^L} \prod_k P_{ik}^{\beta_{ijk}^M + \beta_{ijk}^K} \eta_{ij},$$

where η_{ij} is a constant subsuming production coefficients β, depreciation rates δ, and the interest rate r^f,

7. *The consumption price index of a good from industry k in a given country n is given by*

$$P_{nk} = \left(\sum_i (\tau_{nij} c_{ij})^{-\theta_j} \right)^{-\frac{1}{\theta_j}}.$$

These equilibrium conditions share a similar structure with a wide class of trade models summarized by Costinot and Rodríguez-Clare (2014), with three slight differences. First, the input-output coefficients ($\beta_{ijk}^M + \beta_{ijk}^K$) include not only intermediate input cost shares but also capital service cost shares. This raises the degree of circularity in production. Second, the goods market clearing conditions endogenize demand for capital goods as a function of downstream industry demand. Third, household income used for final consumption is a function of both labor income and capital gains (which is itself endogenous depending on the relative size of capital-intensive industries).

However, it should be clear that these differences manifest in modifications to the system of equations rather than the solution method itself. The dynamic model summarized by these equations is just as well-equipped as conventional models for analyzing the impact of trade liberalization (or other shocks) on the steady state of the global economy.

4 Quantitative Results

In this section I use the open economy model to quantify the gains from trade when capital services are treated as intermediate inputs in production. I begin by describing the sources of data. I show how model parameters such as production function coefficients (on both capital services and intermediate expenses) can be calibrated to the data. I then use the calibrated model to quantify the impact of trade liberalization and productivity shocks.

I find that accounting for the role of capital services in production increases the scale and scope of global value chains. Industries are more inter-dependent than what static model calibrations would have us believe. The per-period welfare gains from trade liberalization are more than double that relative to the static models that treat investment as final use and capital as a primary input (whose prices would be unaffected by trade).

4.1 Data

The main source of data comes from the World Input Output Tables (WIOD). In any given year, this dataset provides estimates of the sale of goods and services from any one industry k in any origin country i to any destination country n for use as either intermediate inputs by industry j, final consumption, or gross fixed capital formation (business investment for production purposes).[6] These datasets have been described and used in prior quantitative work surveyed in Costinot and Rodríguez-Clare (2014) and Antràs and Chor (2021).

One drawback of the WIOD (and virtually all input-output tables) is a lack of information on *which* industries purchased a particular type of capital asset. This obscurity exists for both production and expenditure sides of the table. For example, while we know the value of total investment in computers in each given country in each year, we do not know how much of it was invested in (supplied to) the fishing industry versus the real estate industry. Likewise, in a given industry like fishing, we see total value-added by capital (gross operating surplus), but not the relative value-added by (user costs on) computers versus fishing rods.

I thus supplement the WIOD with data from the U.S. BEA on capital flows across industries. These tables, aptly named Capital Flow tables, are released once every five years with the detailed supply and use tables of the BEA, up until 1997, after which they have become discontinued. These tables contain estimates of the value of new investment by all firms in industry j in the U.S. on capital goods produced by industry k. These data have been used by Atalay (2017) and McGrattan (2017) in RBC settings, but not to my knowledge for the study of the welfare gains from trade.

I concord the BEA's industry classification for the capital flow tables with that of the WIOD into a total of 33 industries. To overcome data availability and reliability issues, I also aggregate the smallest ten countries available in the WIOD and Ireland together with the "rest of the world" region, leaving a total of 33 regions (that I refer to as countries). Results in the rest of the paper are given at this 33-industry and 33-country partition of

[6] According to the System of National Accounts, purchases of durable capital goods such as autos by households count are accounted for under final consumption rather than fixed capital formation. To my knowledge the WIOD datasets abide by this convention.

the global economy.

4.2 Calibration

I primarily use data from the WIOD in 2007 to calibrate my model. One immediate challenge with calibration is that the model requires the global economy to be in steady state. This is potentially far from satisfied in the data. The production and expenditure sides of the input-output tables balance in steady state (equation 8) but not necessarily in the data. Outside of the steady state, investment depends on expectations of future economic conditions. The model's parameters can be calibrated to either the forward-looking steady state implied by investment, or the current-year steady state implied by returns to capital. I choose to calibrate the model to the current-year economic conditions, disregarding future information about the economy contained in investment data.[7]

First, I compute final consumption shares α_{nj} as the share of final consumption by households and the government in country n on output from industry j. Different from pre-existing approaches, these consumption shares do not include expenditures related to gross fixed capital formation in final use. Second, as usual, I compute production function coefficients β^L_{ij} and β^M_{ijk} as the share of country i, industry j's output that is expensed on labor and intermediate inputs k, respectively.

Capital coefficients β^K_{ijk}, however, are harder to calibrate. The WIOD only contains data on the *overall* share of capital value-added in production, $\beta^{VA}_{ij} \equiv \sum_k \beta^K_{ijk}$, as opposed to user costs of capital specific to each type of asset k. BEA's capital flow tables do provide estimates of investment $P_{ik}I_{ijk}$ by asset type k and by using industry j, but only for the U.S. economy. Due to differences in national accounting practices and the lack of any recommendation in the SNA, there is a relative scarcity of comparable data (on either investment $P_{ik}I_{ijk}$ or rental payments $r_{ik}K_{ijk}$) in other countries.

I thus take a more indirect approach to calibrate capital coefficients β^K_{ijk}. I apportion the WIOD's overall capital value-added share in any country i in any industry j, β^{VA}_{ij}, into constituent expenditure shares on different types of capital services k according to the same proportions observed in industry j in the US economy in 1997. For any country i

[7]The steady state of my calibrated model thus does not match investment (new gross fixed capital formation) data in the WIOD because those investments are done on a forward looking basis. For example, outside of steady-state, investment in fishing rods could be even higher than the gross output of all fish. One explanation is that households' future consumption preferences for fish (α) might be increasing. Alternatively, in an open economy, producers in a given fish-exporting country might be anticipating a future reduction in costs of exporting to fish-consuming nations.

and any industry j and asset type k, I compute

$$\beta^K_{ijk} = \beta^{VA}_{ij} \frac{\beta^{K,'97}_{US,jk}}{\beta^{VA,'97}_{US,j}},$$

where, exploiting equation (8), the apportioning shares can be expressed as shares of observed investment on new capital goods

$$\frac{\beta^{K,'97}_{US,jk}}{\beta^{VA,'97}_{US,j}} = \frac{r_{US,k} K_{US,jk}}{\sum_{k'} r_{US,k'} K_{US,jk'}} = \frac{P_{US,k} I_{US,jk} \frac{r^f_{US} + \delta_{US,k}}{\delta_{US,k}}}{\sum_{k'} P_{US,k'} I_{US,jk'} \frac{r^f_{US} + \delta_{US,k'}}{\delta_{US,k'}}}, \tag{10}$$

While relative rental payments (value-added) by different asset types k in industry j are not observed in the data (even in the US), equation (8) relates industry j's rental payments to capital services from k to the industry's investments in capital k, up to a factor $\frac{r^f_{US} + \delta_{US,j}}{\delta_{US,j}}$ that adjusts for the fact that in steady state low-depreciation assets have lower relative investments compared to relative rental payments.[8] Investment data by industry and by supplying asset ($P_{US,k} I_{US,jk}$) come from the BEA's capital flow tables.

I use the BEA's estimates of depreciation rates by asset type j (see the Data Appendix for more details) and set the risk-free rate equal to 0.03 in all countries.

I take import shares directly from the WIOD data. I assume (as the WIOD does) that import shares of country n from country i in industry j do not differ by use (i.e. whether used for capital formation, final consumption, or as intermediate input consumption). I use the same values for trade elasticities as those estimated by Caliendo and Parro (2014). There are a few service industries that are mostly non-traded and lack pre-existing estimates of trade elasticities. For these industries, I set the values of the trade elasticity θ_j to 5, just as Costinot and Rodríguez-Clare (2014) do.

With labor incomes wL, production function coefficients, depreciation rates, a global risk-free rate of 3%, and import shares as mentioned above, I use the system of output market-clearing equations implied by equation (9) to solve for trade imbalances in each country D_n that exactly rationalize the current-year steady state of the global equilibrium.[9]

[8] Whenever rental payments take the form of implicit user costs, such data is not directly observable. If firms carry out fixed capital formation (instead of households in the model), new capital formation is recorded at arms' length but not the internal returns on capital by asset type. The firm's use of capital services is an internal, non-market transaction.

[9] I cannot read D directly from the WIOD data because I remove taxes and subsidies from gross output (so all output is accounted for by intermediates, labor, and capital), and the data on use of output from

4.3 The Gains from Trade

I use the "hat algebra" popularized by Dekle et al. (2008) to solve for the new steady state of the global economy in response to any change in model fundamentals: trade costs, labor size, or productivities.

Proposition 2 (Response of the Global Steady State to Large Shocks) *Given unanticipated, exogenous shocks to trade costs $\hat{\tau}_{nij}$, labor force $\hat{L}_{ij}$, and technology $\hat{A}_{ij}$, and given data from the initial equilibrium on import shares π, labor income wL, trade imbalances D, model coefficients β, α, δ, and a risk-free rate in each country r^f, the new steady state of the global economy can be described by a set of wage changes $\hat{w}_n \equiv \frac{w'_n}{w_n}$ in each country such that the following conditions hold:*

1. *The labor market clears in each country i*

$$\hat{w}_i \hat{L}_i w_i L_i = \sum_k \beta^L_{ik} X'_{ik}, \qquad \forall i,$$

2. *Output markets clear in each industry j in each country i:*

$$X'_{ij} = \sum_n \pi'_{nij} \left[\sum_k \left(\beta^M_{nkj} + \frac{\delta_{nj}}{r^f_n + \delta_{nj}} \beta^K_{nkj} \right) X'_{nk} + \ldots \right.$$
$$\left. \ldots + \alpha_{nj} \left(\hat{w}_n \hat{L}_n w_n L_n + \hat{D}_n D_n + \sum_j \sum_k \frac{r^f_n}{r^f_n + \delta_{nj}} \beta^K_{nkj} X'_{nk} \right) \right],$$

3. *Import shares take the constant-elasticity form:*

$$\pi'_{nij} = \frac{\pi_{nij} (\hat{\tau}_{nij} \hat{c}_{ij})^{-\theta_j}}{\sum_{i'} \pi_{ni'j} (\hat{\tau}_{ni'j} \hat{c}_{i'j})^{-\theta_j}},$$

any given industry involves inventory drawdowns, which has no counterpart in my model. D will also differ from that in the data because investment flows (including imports of capital goods) in the model serve to replenish depreciated capital stock, rather than reflect any forward-looking information contained in the data. Therefore I leave D as a free parameter per country to rationalize the imposed market clearing conditions by industry and country. Despite these differences, the ratios of expenditures to income in the data and in the model have a correlation of 0.68 across the sample of countries.

4. *Changes in unit costs of production in each country i in industry j are given by:*

$$\hat{c}_{ij} = \hat{A}_{ij}^{-1} \hat{w}_i^{\beta_{ij}^L} \prod_k \hat{P}_{ik}^{\beta_{ijk}^M + \beta_{ijk}^K},$$

5. *Changes in the consumption price index of industry k in a given country n are given by:*

$$\hat{P}_{nk} = \left(\sum_i \pi_{nik} (\hat{\tau}_{nik} \hat{c}_{ik})^{-\theta_k} \right)^{-\frac{1}{\theta_k}}.$$

Welfare. *The change in per-period welfare is equal to*

$$\hat{C}_n = \frac{\hat{w}_n \hat{L}_n w_n L_n + \sum_j \sum_k \frac{r_n^f}{r_n^f + \delta_{nj}} \beta_{nkj}^K X'_{nk}}{w_n L_n + \sum_j \sum_k \frac{r_n^f}{r_n^f + \delta_{nj}} \beta_{nkj}^K X_{nk}} \prod_k \hat{P}_{nk}^{-\alpha_{nk}} \tag{11}$$

$$= s_n^L \cdot \underbrace{\frac{\hat{w}_n \hat{L}_n}{\prod_k \hat{P}_{nk}^{\alpha_{nk}}}}_{\text{real labor income}} + (1 - s_n^L) \cdot \underbrace{\frac{\sum_k \mu_{nk} \hat{X}_{nk}}{\prod_k \hat{P}_{nk}^{\alpha_{nk}}}}_{\text{real capital gains}}, \tag{12}$$

where μ_{nk} denotes country n's share of capital gains in industry k (relative to other industries):

$$\mu_{nk} \equiv \frac{\sum_j \beta_{nkj}^K \frac{r^f}{r^f + \delta_{nj}} X_{nk}}{\sum_{k'} \sum_j \beta_{nk'j}^K \frac{r^f}{r^f + \delta_{nj}} X_{nk'}},$$

and s_n^L denotes the share of country n's consumption from labor income (as opposed to capital gains)

$$s_n^L \equiv \frac{w_n L_n}{w_n L_n + \sum_j \sum_k \frac{r_n^f}{r_n^f + \delta_{nj}} \beta_{nkj}^K X_{nk}}.$$

Equation (12) decomposes the welfare change into two margins. The first is the change in real labor income—the traditional "welfare gains from trade" popularized by Arkolakis et al. (2012). The second margin is the change in real capital gains, which is new. Each period, a proportion of value-added by capital is consumed by households rather than invested, and any equilibrium change to value-added by capital thus affects real consumption.[10]

I simulate a 10 percent reduction in trade costs across all countries in all industries, $\hat{\tau}_{nij} = 0.9$, and use Proposition 2 to solve for the resulting welfare changes across countries in the new steady state of the global economy.[11] I contrast these predictions for welfare with results obtained from a conventional calibration of model parameters to the same input-output data, as in Costinot and Rodríguez-Clare (2014). In most pre-existing quantitative research on the gains from trade, capital is treated as a primary input (assumed to have a unit cost that moves in tandem with the wage w_n) and investment is treated as a final use in consumption. I re-calibrate my model based on these standard assumptions, making adjustments for what is considered primary factor ("labor") income in each country so that gross output per country per industry remains the same across calibrations.

Figure 2 plots the gains from trade liberalization in each country across the two different ways of interpreting capital. In the conventional calibration (in green), the gains from a 10 percent trade liberalization average 5.2 percent across countries. In my preferred setting where the rental rates of capital services in production are linked to the investment prices of new capital assets, the gains from trade average 12.8 percent across countries, at more than double the standard estimates.

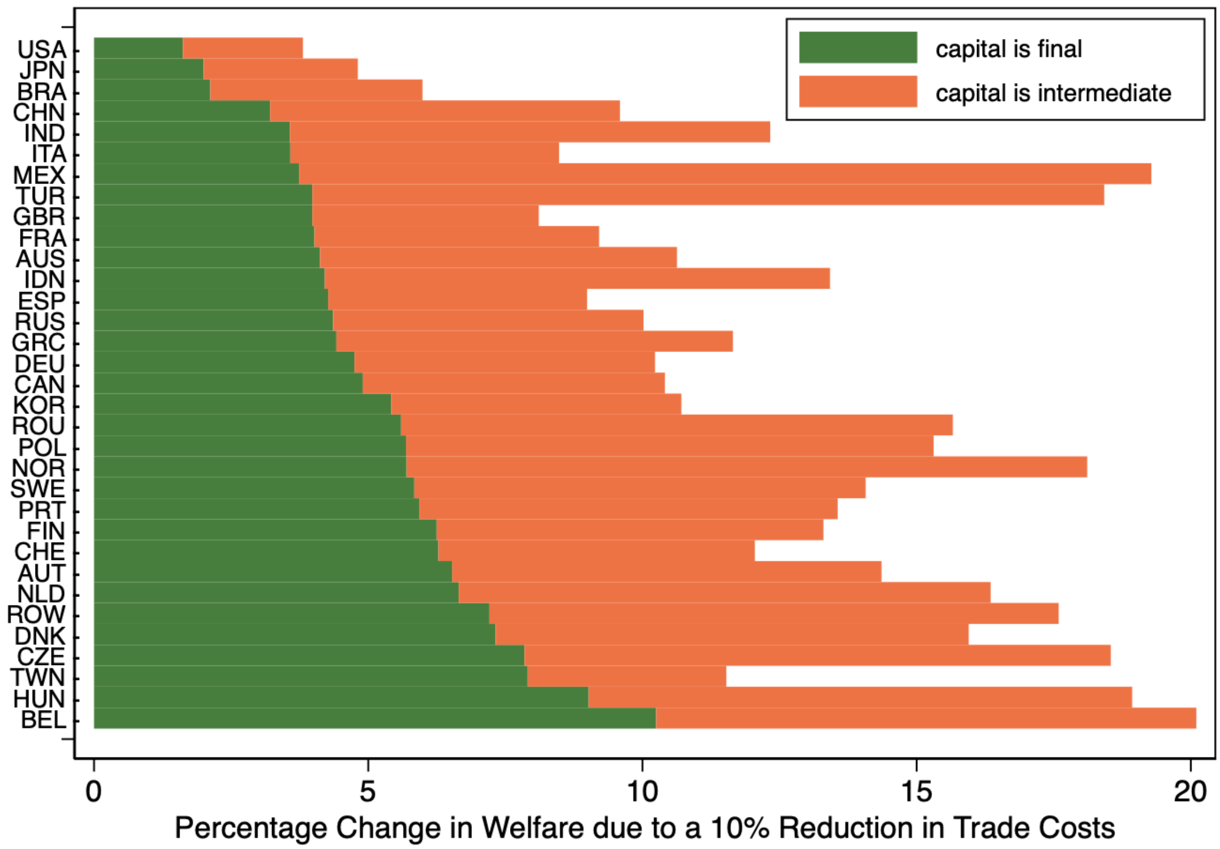
Finally, in Appendix Figure C.3, I use equation (12) to break down the orange bar detailing the total change in per-period welfare into the change in real labor income (denoted in blue) and the change in real capital gains (denoted in red). There are two drivers of the relative sizes of each margin. The most obvious driver is the share of a country's consumption in the pre-existing equilibrium from labor income versus from capital gains. In countries where the share of consumption from capital gains is much larger (Mexico), the contribution of the capital gains channel is clearly larger.

Interestingly, trade liberalization also generates, on average, a reallocation from labor income to capital gains income. Figure C.4 shows a scatterplot comparing the change in real capital gains income versus the change in real labor income. Most countries lie above the 45 degree line, experiencing a greater change in capital gains income versus labor

[10]Note that capital gains does not equal value-added by capital as a share of total value-added is plowed back into investment to maintain capital stocks in steady state. As the risk-free rate approaches zero, capital gains becomes negligible. In the model calibration, on average 22% of a country's consumption expenditures are financed from capital gains in the initial steady state.

[11]I do consider a return-to-autarky counterfactual, as is typically standard in quantitative trade models, for two reasons. First, it would involve removing current trade imbalances. Second, the level of disaggregation (33-industries) I pursue in my calibration generates industries in which a country has a zero self-import share (i.e. it consumes from other countries but not from itself). Note that these challenges would persist regardless of how capital is treated.

Figure 2: The Gains from Trade Liberalization: Comparison Across Models



Notes: This figure plots the per-period welfare gains from trade (in percentage terms: $100(\hat{C}_n - 1)$) in each country in the new global steady state of the economy due to a 10% reduction in trade costs across all country pairs $n \neq i$ in all industries. The values denoted in green are the welfare gains when capital is treated an independent factor of production and investment is final use (existing models). The values denoted in orange are the welfare gains when capital services are recognized as intermediate inputs in production and the assets purchased to invest in capital formation are traded as in the WIOD data.

income. The results predict that trade liberalization would generate industry reallocations in each country that increase the global share of income from capital rather than from labor. Note that this reallocation does not require capital and labor shares in *production* to have changed at all. In fact, in the Cobb-Douglas economy, the share of labor costs and the share of capital service costs remain invariant at the country-industry level.

Comparison with existing estimates. In their handbook chapter, Costinot and Rodríguez-Clare (2014) work out an back-of-the-envelope extension where they re-consider the nature of physical capital. In their baseline quantitative results, new capital formation is final use and prices of existing capital services move in tandem with wages. In this extension they instead reallocate one-third of all value added in each industry and country to input industries in proportion to the current use of intermediate inputs. For example, suppose that the costs of producing fish are broken up into 60% labor, 10% bait (an intermediate input), and 30% fishing rods (services of capital equipment). Their benchmark assumption would have value added (by the composite primary factor of production) be 90% and cost of bait 10%. In their extension, they would re-assign one third of value-added to expenditures on the intermediate-supplying industry and assume that value added (again, by a composite single factor of production) is 60% and the cost of bait 40%.

Costinot and Rodríguez-Clare (2014) find that the gains from trade under their extension are on average 28% larger than their baseline multi-sector estimates. While notable, this is however a much smaller increase compared to my finding that the gains are 145% larger when the user cost of capital services are allowed to fall with respect to globalization.

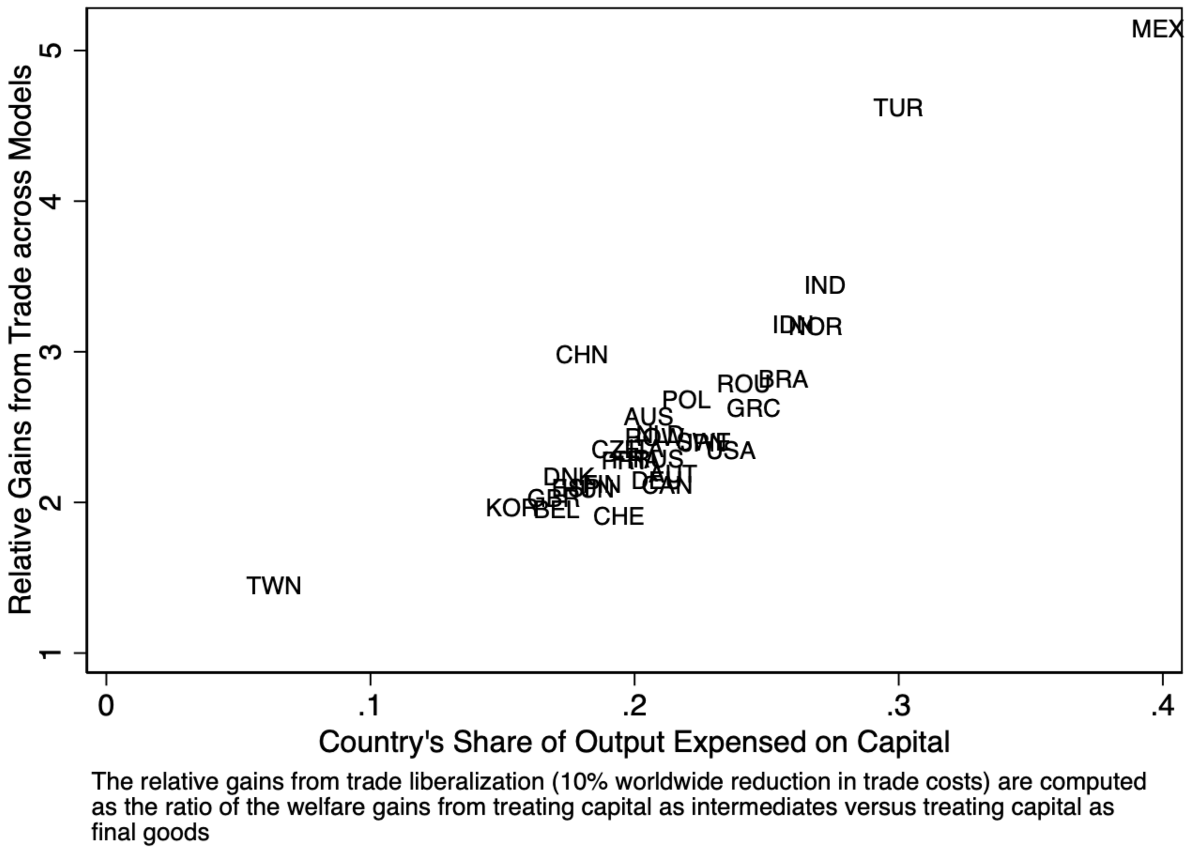
There are several reasons for this difference. They presume that one-third of value-added in each industry in each country is due to capital, whereas I use data from the WIOD socioeconomic accounts on value-added by labor by country to construct exact capital shares of value added. In the data the share of value-added by capital is higher, at almost one-half. I also take the additional step of adjusting final consumption expenditure shares in each country by removing investment (GFCF) as a column in final use.[12] Perhaps most crucially, I apportion capital value-added to *capital-supplying* industries whereas they apportion capital value-added to *existing* intermediate input-supplying industries. Value chains in my framework thus link up capital-supplying industries and capital-using industries, whereas their steps only serve to strengthen pre-existing intermediate input linkages.

4.4 Missing Welfare Gains Rise with Capital Intensity in Use

The increased welfare gains in my model relative to the static benchmark are far from uniform across countries. Figure 3 shows that these "missing" welfare gains are relatively larger in countries that are more capital-intensive. Take for example, Mexico, with an industry structure that relies heavily on capital for production. In the dynamic model, trade liberalization lowers the costs of imported capital goods, which under perfect competition lowers the rental prices of capital services, and therefore lowers the output prices of Mexican producers as well as the consumption prices of Mexican households. In the

[12] Though, because, capital goods are more traded than final consumption goods, this adjustment would actually serve to lower the gains from trade in my model relative to theirs, all else equal.

Figure 3: Capital Intensity in Use Explains the Increased Gains from Trade



Notes: This figure plots the ratio in the predicted welfare gains from trade in the two different model calibrations in Figure 2 against each country's overall capital intensity in production.

benchmark static model, capital is a primary input and trade would thus have no impact on the prices of capital services faced by Mexican producers.

Another way to interpret the results in this section is not that countries differ fundamentally in their capital shares, but that the statistical measurement of intermediate input use across countries might differ due to national accounting practices (such as the treatment of R&D and intellectual property products outlined in Section 2.2). Seen in this light, benchmark results on the quantitative gains from trade are biased downwards for countries with accounting practices that skew towards capitalization (the "missing gains" in these countries are higher). The dynamic framework corrects for this bias by treating intermediate inputs and capital services symmetrically in production. Consistent with this interpretation, I find a negative relationship between intermediate input shares of output and capital value-added shares of output across countries. Appendix Figure C.2

shows that indeed, countries like Mexico that have high expenditure shares on capital also have low expenditure shares on intermediates (and vice versa for Taiwan and Korea).

4.5 Missing Welfare Impacts Rise with Capital Intensity in Supply

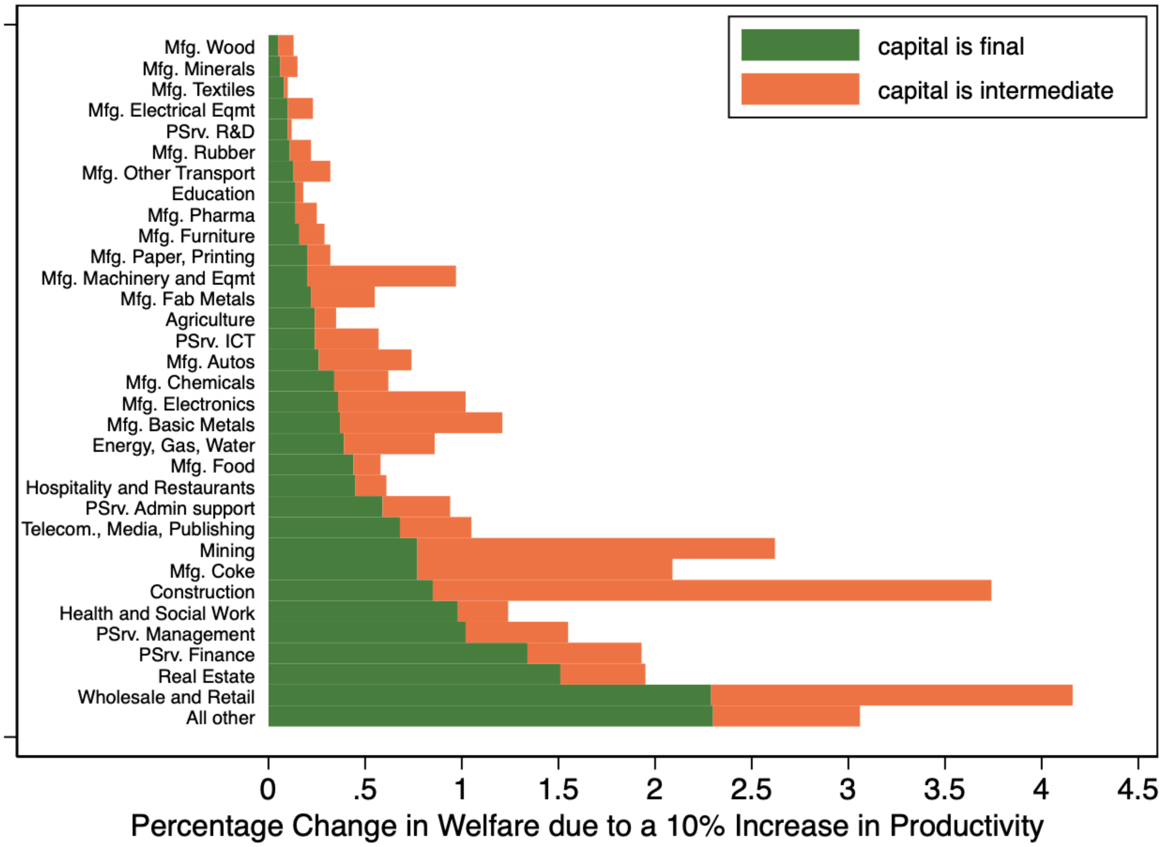
Thus far, this quantitative section has analyzed the impact of a widespread trade liberalization episode. Increased welfare gains are biased towards countries and industries with the highest capital shares in *use* (expenditure shares).

In this subsection I turn away from trade and consider the domestic welfare impact of industry-specific productivities shocks in the US economy. Instead of using Proposition 1 to derive the exact local impacts on welfare, I retain the same open economy calibration as before (where the US has a foreign import share of around 5%). I continue to use Proposition 2 to solve out for the set of exact changes in steady-state variables given the set of US-specific productivity shocks. I compare the impact of a productivity shock in a given US industry on US welfare across the two model calibrations (one treating capital services as intermediate and another treating capital as a primary factor), shocking each industry one at a time. Given the relatively closed nature of the US economy, most of the impacts of the productivity shock manifest domestically, so I focus on variation across industries rather than countries.

Figure 4 shows that the model with capital treated as an intermediate input yields US welfare increases that are on average more than double that in the model where capital is a primary input. The magnitudes of the impact on welfare depend obviously on the size of the industry, but the relative difference between the two models (orange bar relative to the green bar) is size-free and reveals substantial variation across industries. Consistent with intuition, the largest relative differences feature in industries that produce mostly capital goods, such as the manufacture of machinery and equipment, ICT services, the manufacture of autos, electronics, mining, and construction.

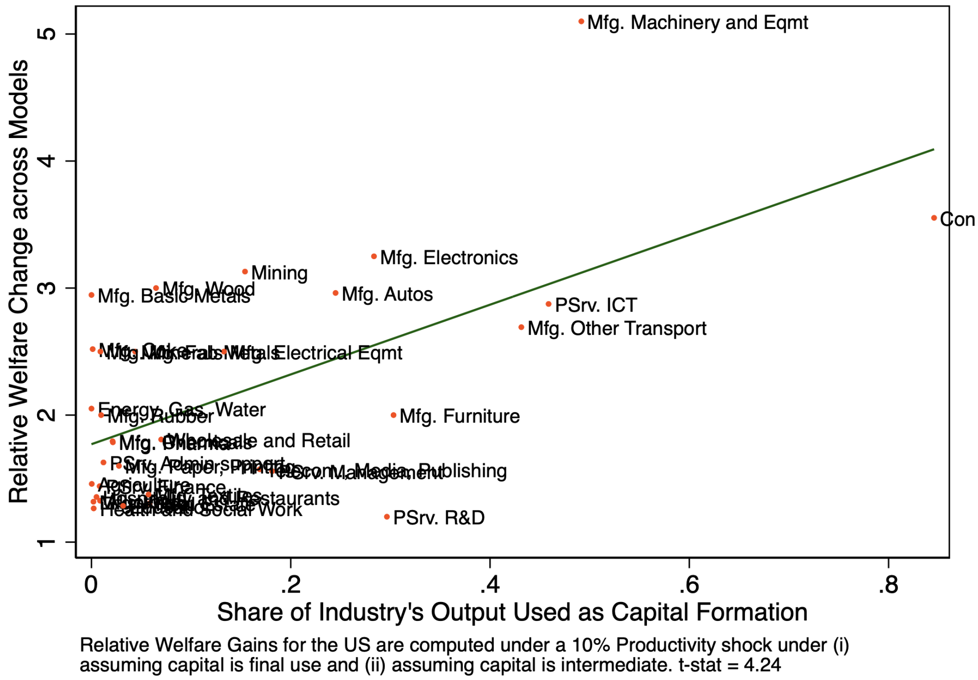
Finally, Figure 5 shows that indeed, industries with a higher share of output supplied for capital formation are industries with the highest *relative* welfare impacts across the two models. Recognizing capital formation as dynamic intermediate use raises the upstreamness of capital-supplying industries. This causes the estimated impact of a productivity shock on capital-supplying industries to be both larger and more widespread. The correlation is not perfect because the x-variable captures only the first-order importance of that industry's output for capital formation rather than all the higher-order percolation effects, such as its use by any other industries whose output is then supplied for capital

Figure 4: The Impact of Productivity Shocks: Comparison Across Models



Notes: This figure plots the per-period impact of productivity shocks on US welfare (real consumption change in percentage terms: $100(\hat{C}_n - 1)$) in the new global steady state of the economy due to a 10% increase in productivity in a row industry in the US. The values denoted in green are the welfare gains when capital is treated an independent factor of production and investment is final use (existing models). The values denoted in orange are the welfare gains when capital services are recognized as intermediate inputs in production and the assets purchased to invest in capital formation are traded as in the WIOD data. The unweighted average ratio of the orange to the green bar is 2.11 across industries, indicating a more than doubling of the impact of productivity shocks on welfare.

Figure 5: Capital Intensity in Supply Explains the Increased Response of Welfare to Productivity



Notes: This figure plots the ratio in the predicted welfare gains from productivity increases in the two different model calibrations in Figure 4 against each US industry's capital intensity in supply (share of industry output supplied for gross fixed capital formation).

formation.[13]

5 Conclusion

Many existing quantitative cross-sectional models in trade and macro treat capital as a primary input. This is at odds with the papers' focus on long-run changes in the economy in response to shocks. When a trade or productivity shock lowers the price of an *expensed* intermediate input, all industries that the input supplies benefit from the lower prices. But when a shock lowers instead the price of a *capitalized* investment asset, none of the downstream industries benefit because investment is treated as final use.

This paper lays out a theoretical framework to reconcile the disconnect and treat the use of capital services symmetrically with the use of intermediate inputs in production.

[13]Indeed, Proposition 1 gives the exact sufficient statistics for an economy in autarky. In an open economy setting the presence of general equilibrium impacts prevent a similar closed-form representation.

A capital input is simply an intermediate input that doesn't depreciate fully within the accounting period. I develop a dynamic general equilibrium model where capital coefficients in production can be identified from investment flows data published by the BEA (in conjunction with standard input-output tables). Inter-industry relationships can be summarized by an augmented input-output matrix with coefficients that capture the costs of both intermediate inputs and capital services. Despite the dynamics in the model, the augmented input-output coefficients act as sufficient statistics. The exact same quantitative machinery (e.g. exact hat algebra, as in Dekle et al., 2008 and summarized by Costinot and Rodríguez-Clare, 2014) can be used to compute per-period steady-state outcomes of the dynamic model, just as it can be used to compute the per-period equilibrium outcomes from a static, infinitely-repeated one-period model.

Quantitatively, cross-industry linkages from the supply and use of capital services matter for both the gains from trade and the impact of industry-level productivity shocks. In both cases I find effects that are more than double what would be computed from conventional calibrations. Perhaps unsurprisingly, the differences across models are greatest for industries that consume higher amounts of capital services and for industries that supply a greater share of output used for capital formation. However, given the higher-order interactions and feedback effects in a full multi-country input-output loop and general equilibrium effects, the correlations are not exact. I develop closed-economy formulas for re-evaluating measures of centrality that could serve as sufficient statistics for the welfare impact of productivity shocks.

While it may seem at first glance that the dynamic model requires more assumptions, static models in fact carry just as many assumptions, albeit more implicitly. For example, counterfactuals in static models assume away growth and the calibration of such models to a given cross-section of the data would interpret what might be temporary production and consumption patterns as primitives. My paper has kept model assumptions and complexity to a minimum in order to demonstrate the first-order impact of modeling capital service flows in global production networks. But the dynamic framework can accommodate numerous extensions, such as FDI, growth, and different risk profiles across capital assets. Future research could also model transition dynamics, or measure the heterogeneous impacts of trade liberalization on labor and capital income across countries.

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APPENDICES

A Data Construction and Calibration

World Input-Output Tables. These data come from the 2016 release of the World Input Output Database (Timmer et al., 2015). I aggregate the native industry classification in the WIOD to a 33-industry classification to be consistent with quantitative models calibrated to previous releases of the database (Costinot and Rodríguez-Clare, 2014), and to facilitate concordance with the BEA's industry and commodity nomenclature in its capital flow tables. The 33 industries are shown in Table A.1, along with accompanying industry-level data from the WIOD, such as the share of output consumed as capital and the share of production costs on capital (value-added by capital), and trade elasticities and depreciation rates (see paragraphs below).

There are 45 countries in this version of the WIOD. Because industry-level data are more likely to be measured with error (and in fact, sometimes missing) for smaller countries, I fold the 10 smallest countries (by GDP, they are Bulgaria, Cyprus, Estonia, Croatia, Lithuania, Luxembourg, Latvia, Malta, Slovakia, Slovenia) plus Ireland into the rest-of-the-world aggregate. This leaves me with 33 regions that I work with in the paper. Their names and letter abbreviations are given in Table A.2, along with some country-level characteristics from the WIOD data.

The world input output tables in the WIOD report only total value-added by industry-country, and not the respective labor and capital shares. I use the complementary socio-economic accounts data in the WIOD, which contain separate estimates of labor compensation per industry. I define the labor share per industry in each country as total labor compensation as a share of total value added, and capital shares as 1 minus the labor share. Socioeconomic data are missing in 2007 for a few country and industry pairs. For these missing data cases I set the capital share to the global capital share of that industry among all countries that report labor compensation and value-added data.

I replace a negative values as entries in the WIOD. The fuel manufacturing industry in Brazil reports negative value-added. While this could technically occur (so the industry makes a loss as a whole), to ease the burden on the theoretical model, I reset value-added in the fuel manufacturing industry to a positive 3% of gross output, its historical value over other years in the WIOD. Six other country-industries report negative gross fixed capital formation. This poses a problem for the model whenever the negative investment value is larger than household and government consumption combined (so final expenditure in the industry is negative). This occurs for Korea in basic metal manufacturing. For this entry, I replace the value of investment to be the negative value of household and government consumption, so total final use (as interpreted through the version of the model where investment is final use) is 0 instead of negative (see the paragraph on consumption shares below).

Production Shares. To keep the model ingredients simple I model only intermediate inputs, labor, and capital services in the production function. I make a few adjustments to the input-output

Table A.1: Industries and their economic characteristics in 2007

Industry Description	δ_k	θ_k	π_k	share of output consumed: as capital	as utility	share of production costs on capital	on labor
Agriculture	0.32	8.11	0.09	0.02	0.34	0.21	0.36
Mining	0.06	15.72	0.39	0.05	0.01	0.50	0.12
Mfg. Food	0.14	2.55	0.13	0.00	0.60	0.15	0.12
Mfg. Textiles	0.14	5.56	0.37	0.01	0.49	0.12	0.15
Mfg. Wood	0.14	10.83	0.16	0.04	0.05	0.12	0.17
Mfg. Paper, Printing	0.14	9.07	0.15	0.01	0.10	0.13	0.20
Mfg. Coke	0.14	51.08	0.22	0.00	0.25	0.16	0.04
Mfg. Chemicals	0.14	4.75	0.31	0.01	0.15	0.15	0.10
Mfg. Pharma	0.14	4.75	0.37	0.01	0.35	0.21	0.12
Mfg. Rubber	0.14	1.66	0.24	0.02	0.10	0.12	0.19
Mfg. Minerals	0.14	2.76	0.12	0.01	0.05	0.13	0.14
Mfg. Basic Metals	0.14	7.99	0.26	0.01	0.01	0.17	0.14
Mfg. Fab Metals	0.09	7.99	0.18	0.10	0.05	0.09	0.15
Mfg. Electronics	0.25	10.6	0.56	0.25	0.14	0.15	0.18
Mfg. Electrical Eqmt	0.12	10.6	0.36	0.18	0.16	0.17	0.21
Mfg. Machinery and Eqmt	0.13	1.52	0.35	0.41	0.04	0.15	0.24
Mfg. Autos	0.14	0.37	0.37	0.25	0.27	0.15	0.17
Mfg. Other Transport	0.11	0.37	0.44	0.37	0.13	0.23	0.29
Mfg. Furniture	0.13	5	0.36	0.19	0.36	0.13	0.29
Energy, Gas, Water	0.02	5	0.03	-0.01	0.22	0.22	0.11
Construction	0.03	5	0.01	0.78	0.02	0.07	0.15
PSrv. Finance	0.50	5	0.08	0.01	0.36	0.27	0.28
Hospitality and Restaurants	0.32	5	0.06	0.00	0.72	0.18	0.32
PSrv. ICT	0.33	5	0.13	0.39	0.06	0.16	0.43
PSrv. Management	0.50	5	0.09	0.11	0.07	0.16	0.40
PSrv. R&D	0.20	5	0.11	0.17	0.14	0.19	0.37
PSrv. Admin support	0.50	5	0.11	0.02	0.17	0.26	0.37
Education	0.32	5	0.01	0.01	0.89	0.11	0.64
Health and Social Work	0.32	5	0.00	0.00	0.93	0.09	0.53
All other	0.32	5	0.01	0.01	0.85	0.15	0.49
Real Estate	0.03	5	0.00	0.05	0.69	0.70	0.07
Telecom., Media, Publishing	0.09	5	0.06	0.08	0.38	0.33	0.22
Wholesale and Retail	0.10	5	0.11	0.06	0.40	0.23	0.34

Industries come from a slight aggregation of the WIOD nomenclature. Depreciation rates are taken from the BEA and from Corrado et al. (2009) (see paragraph on Depreciation below). Data shown are averages across countries within manufacturing sectors. Trade Elasticities are taken from Caliendo and Parro (2014). Remaining data come directly from the WIOD. Import shares are the total share of consumption purchased from other countries.

Table A.2: Countries and their economic characteristics in 2007

Abbreviation	Country Name	GDP	Gross Output	Capital Intensity in Production	Import Share
AUS	Australia	912	1894	0.21	0.06
AUT	Austria	345	694	0.21	0.15
BEL	Belgium	422	940	0.17	0.19
BRA	Brazil	1211	2381	0.26	0.05
CAN	Canada	1373	2618	0.21	0.10
CHE	Switzerland	459	939	0.19	0.12
CHN	China	3495	10590	0.18	0.07
CZE	Czech Republic	172	444	0.19	0.18
DEU	Germany	3099	6250	0.21	0.11
DNK	Denmark	271	552	0.18	0.17
ESP	Spain	1333	2945	0.18	0.09
FIN	Finland	224	480	0.19	0.13
FRA	France	2394	4658	0.20	0.09
GBR	United Kindgom	2664	5131	0.17	0.08
GRC	Greece	281	506	0.25	0.10
HUN	Hungary	120	278	0.18	0.26
IDN	Indonesia	455	893	0.26	0.09
IND	India	1135	2290	0.27	0.09
ITA	Italy	1982	4271	0.20	0.08
JPN	Japan	4311	8460	0.23	0.05
KOR	Korea	1014	2462	0.15	0.11
MEX	Mexico	1003	1728	0.40	0.11
NLD	Netherlands	750	1475	0.21	0.15
NOR	Norway	357	646	0.27	0.09
POL	Poland	376	849	0.22	0.13
PRT	Portugal	209	429	0.20	0.11
ROU	Romania	152	309	0.24	0.12
RUS	Russia	1114	2194	0.21	0.04
SWE	Sweden	431	872	0.23	0.13
TUR	Turkey	581	1199	0.30	0.10
TWN	Taiwan	392	920	0.06	0.20
USA	United States	14478	26088	0.24	0.04
ROW	Rest of the World	6917	15829	0.21	0.14

Countries come from a slight aggregation of the WIOD nomenclature. All data taken directly from the WIOD. GDP and Gross Output are in billions of 2007 USD. Capital Intensity in production is measured as capital value-added as a share of gross output.

data to make it consistent with the model. I drop the follow 'rows' from the tables: taxes and subsidies, cif / fob adjustments for exports, direct purchases abroad by residents, purchases on the domestic territory by non-residents, and international transport margins.

Consumption Shares. Change in inventories exists as a final column in the WIOD but this is misleading because it is an adjustment to make expenditures add up to total output in a given row. Each other column in the WIOD for a given row (a given producing industry-country) refers to consumption values including the portion that was drawn down from inventories. I thus remove the change in inventories column as a final use column. This leads three final consumption categories: (i) by households, (ii) for gross fixed capital formation, and (iii) by the government. In the version of the model where capital is a dynamic intermediate good, I compute demand-side Cobb-Douglas consumption coefficients across industries by using (i) and (iii). In the version of the model where investment is part of final use, I compute demand-side Cobb-Douglas consumption coefficients across industries by using (i), (ii), and (iii).

BEA Capital Flow Tables. I use the Capital Flow Tables provided by the BEA in 1997 (see Meade et al., 2003 for more details). These data show the amount of new investment made by 123 producing industries (j) on 180 different types of capital assets (k) in that year. I aggregate this data into the 33-industry classification used throughout the paper, and take these new investment values as $P_{US,k}I_{US,jk}$ in equation (10). Using an assumed interest rate of 0.03 and depreciation rates by asset type k below, I am able to compute expenditures on capital services of type k for each using industry j as a share of capital value-added.

Trade Elasticities and Import Shares. I use the same values of trade elasticities as Costinot and Rodríguez-Clare (2014), which in turn come from estimates by Caliendo and Parro (2014). For industries without a pre-existing estimate, I set the value of the trade elasticity to equal 5. I compute import shares π_{nij} as the share of country n's expenditures on output from an industry j (for all purposes—intermediates, final consumption, and capital formation) from producers in country i. Both the WIOD data and the model follow the import proportionality assumption: import shares are the same regardless of the way the output is used.

Depreciation Rates. I assume that a given type of capital asset k depreciates at the same rate regardless of the country n or industry j in which it is deployed. I primarily use the US BEA's estimates of depreciation rates by asset type k, available at `https://apps.bea.gov/national/pdf/BEA_depreciation_rates.pdf`. I develop a concordance between the BEA's asset classification and the 33-industry classification in the paper. Whenever there are multiple assets that map into an industry, I take the average depreciation rate among those assets. Some industries (such as agriculture and various professional services) in my classification does not match to any available asset type in the BEA publication. I set the depreciation rates for assets produced by these industries as follows. I assume assets from the construction industry depreciate at the same rate as assets from the real estate industry (0.03). Following Corrado et al. (2009) and the empirical research cited therein, I assume that assets produced by the ICT professional services industry depreciate at rate 0.33. I assume that assets produced by the R&D industry depreciate at 0.2. I assume that assets produced by the management and administrative support industries depreciate at rate 0.5 (the average of the depreciation of brand equity and firm-specific resources in Corrado et al., 2009). I divide remaining industries without depreciation rate estimates into either manufacturing or non-manufacturing sectors. I set the depreciation rate of assets produced by these industries to the average depreciation rate among industries in the respective manufacturing or non-manufacturing sectors (excluding electricity, real estate, construction and mining industries), which are 0.29 and 0.14, respectively.

Trade Deficits. Rather than take trade deficits directly from the WIOD data, I solve for the deficits in each country that rationalize the other calibrated parameters. Specifically, under Definition 2, the steady state of the global economy can be described by:

$$w_i L_i = \sum_k \beta_{ik}^L X_{ik}, \qquad \forall i,$$

$$X_{ij} = \sum_n \pi_{nij} \left[\sum_k \left(\beta_{nkj}^M + \frac{\delta_{nj}}{r_n^f + \delta_{nj}} \beta_{nkj}^K \right) X_{nk} + \alpha_{nj} \left(w_n L_n + D_n + \sum_j \sum_k \frac{r_n^f}{r_n^f + \delta_{nj}} \beta_{nkj}^K X_{nk} \right) \right], \quad \forall i, j,$$

where all variables and parameters in the equations above except for output X and deficits D are calibrated or taken directly from the data. The second equation is a system of $N \times K$ equations in as many unknowns X_{ij}, but the first equation is a system of N equations that puts a constraint on the scale of X_{ij} in each country i. Therefore, the set of N unknowns D_n (deficits in each country) can be solved for to exactly rationalize this system of equations (essentially, $N \times (K+1)$ equations in $N \times (K+1)$ unknowns).

Technically, deficits and output can be directly read from the data, but this would generate several inconsistencies with the assumptions in the model. First, the model assumes that the economy is in steady state, whereby investment is used solely to replenish depreciated capital. In the data, however, investment can differ due to its forward looking nature. I do not use any investment data from the world input-output tables, and thus investment in my model is consistent with the steady state. This potentially affects each industry's output and each country's deficits because countries investing more today (through importing more capital goods) would garner larger deficits. Second, I remove taxes and subsidies and other minor corrections when calibrating production parameters, so output in the data will not match perfectly with output in the model. Third, there are inventory drawdowns that affect a country's total consumption versus total output in any period. Because I do not model inventories in the mapping from the data to the model, output and deficits will differ again between the data and the model.

In summary, I take a minimum set of data

B Proofs

Proof of Proposition 1. Because preferences and production are both Cobb-Douglas, sectoral allocations will not change in response to productivity shocks. That is, given L, equation 5 admits only one solution for industry output X_j as a function of coefficients β and α, but not technology A. Household income consists of wage and capital gains income but the wage is the numeraire and capital gains income is the sum of a constant fraction of X_j in each industry j, so overall income remains unchanged across counterfactuals.

Therefore the only equilibrium impact of productivity shocks on welfare will be through the price index dual to consumption, a function of P_j. To solve for the impact on P_j, the cost minimization problem of the firm in industry j facing a price P_k for intermediate inputs and a rental price (or user cost) r_k for capital services and a numeraire wage leads to unit costs (which equal prices under perfect competition) is given by

$$P_j = A_j^{-1} \left(\prod_k P_k^{\beta_{jk}^M} r_k^{\beta_{jk}^K} \right) \prod_k \left((\beta_{jk}^M)^{-\beta_{jk}^M} (\beta_{jk}^K)^{-\beta_{jk}^K} \right).$$

Now using the fact that $(r^f + \delta_k) P_k = r_k$ in steady state, the price index in industry j can be simplified into

$$P_j = A_j^{-1} \left(\prod_k P_k^{\beta_{jk}^M + \beta_{jk}^K} \right) \eta_j, \tag{13}$$

where η_j is a constant given by

$$\eta_j \equiv \left((\beta_{jk}^M)^{-\beta_{jk}^M} \left(\frac{\beta_{jk}^K}{r^f + \delta_k} \right)^{-\beta_{jk}^K} \right).$$

Differentiating equation (13) yields

$$\mathrm{d}\log P_j = -\,\mathrm{d}\log A_j + \sum_k (\beta_{jk}^M + \beta_{jk}^K)\,\mathrm{d}\log P_k$$

which in matrix notation (using $\boldsymbol{B}_{jk} \equiv \beta_{jk}^M + \beta_{jk}^K$) is

$$\mathrm{d}\log \boldsymbol{P} = -\,(\boldsymbol{I} - \boldsymbol{B})^{-1}\ \mathrm{d}\log \boldsymbol{A}$$

Per-period welfare is given by the dual to the final consumption index

$$C = \prod_{j=1}^{K} P_j^{-\alpha_j},$$

so that differentiating yields the expression in the proposition

$$\mathrm{d}\log C = -\boldsymbol{\alpha}'\,\mathrm{d}\log \boldsymbol{P} = \boldsymbol{\alpha}'\left(\boldsymbol{I}-\boldsymbol{B}\right)^{-1}\,\mathrm{d}\log \boldsymbol{A}.$$

■

Proof of Corollary 1. This comes directly from solving for industry output $\{X_j\}_j$ using the system of equations (5) in Definition 1. Equation (5) can be written in matrix form as

$$\boldsymbol{X} = \boldsymbol{\Upsilon}'\boldsymbol{X} + \boldsymbol{\alpha}L,$$

where $\boldsymbol{X}$ is a $K \times 1$ vector of industry output. Rearranging, inverting for $\boldsymbol{X}$, and dividing by GDP, a scalar, yields

$$\frac{\boldsymbol{X}}{GDP} = \left(\boldsymbol{I}-\boldsymbol{\Upsilon}'\right)^{-1}\boldsymbol{\alpha}\frac{L}{GDP},$$

and taking the transpose of the right-hand-side expression yields the result in the corollary. ■

Proof of Proposition 2. These expressions come directly from relating the definition of the open economy steady state (Definition 2) under the new fundamentals L_i', A_{ij}', and τ_{nij}' (the $'$ notation is used to distinguish the new from the old variables) to the definition of the steady state under the old fundamentals L_i, A_{ij}, and τ_{nij}. Let the 'hat' notation denote exact proportional changes, where for any variables Y and Y' before and after the steady state: $\hat{Y} \equiv \frac{Y'}{Y}$. The first two conditions come directly from the corresponding expressions in Definition 2. The third condition comes from expressing

$$(\tau_{nij}'c_{nij}')^{-\theta_j} = \pi_{nij}(\hat{\tau}_{nij}\hat{c}_{nij})^{-\theta_j}(\sum_{i'}\tau_{ni'j}c_{ni'j})^{-\theta_j}$$

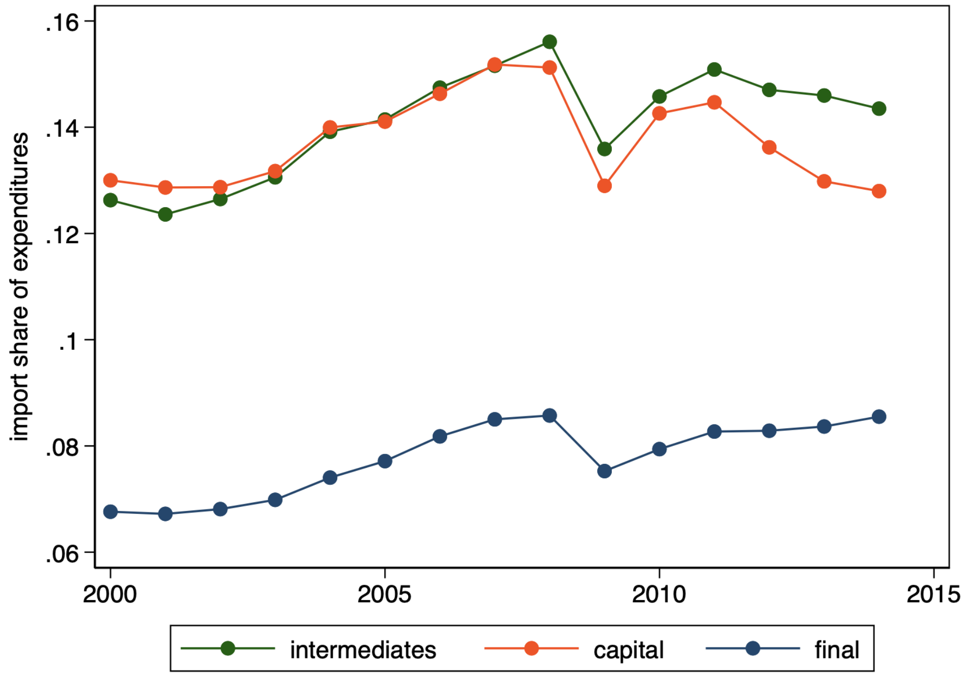
in both the numerator and denominator of the equivalent expression in Definition 2. The forth expression comes from applying hat algebra to the unit cost Cobb-Douglas function in equation (13), and the fifth expression comes from a similar hat algebra application to the unit consumption price index of industry k in country n:

$$P_{nk} \equiv \left(\sum_i \tau_{nik}c_{ik})^{-\theta_k}\right)^{-\frac{1}{\theta_k}}.$$

Finally, to compute welfare changes in steady state, note that real consumption is given by income (sum of labor and capital gains) divided by the final consumption price index. Therefore

$$C_n \equiv \frac{w_nL_n + \sum_j\sum_k \frac{r_n^f}{r_n^f+\delta_{nj}}\beta_{nkj}^K X_{nk}}{\prod_k P_{nk}^{\alpha_{nk}}}$$

Figure C.1: Capital Goods are as tradable as Intermediate Goods

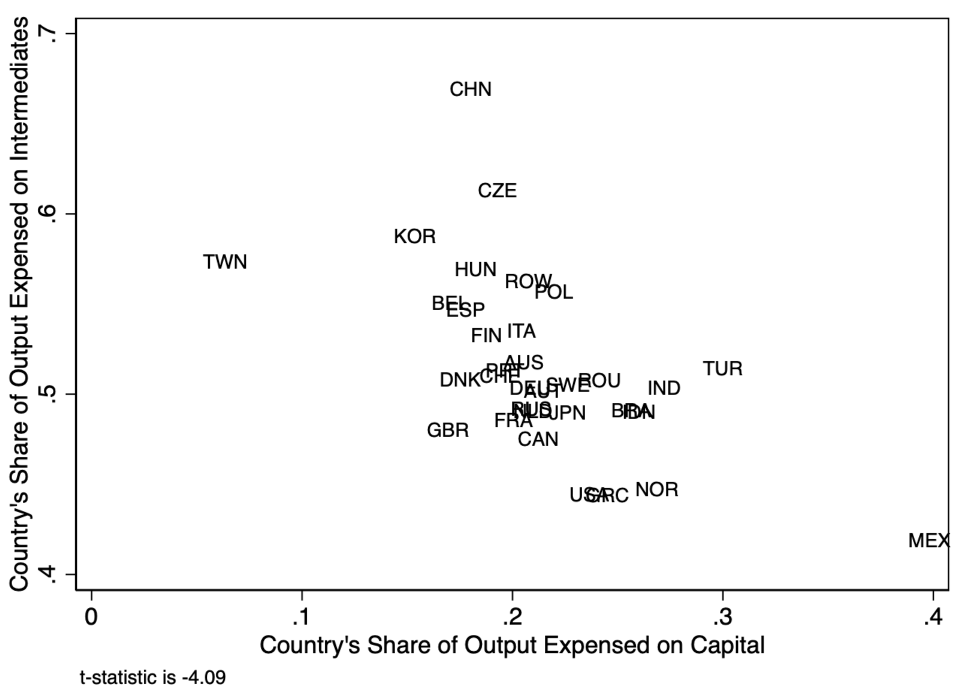


Notes: This figure plots the share of expenditures that are imported by type of use: (i) intermediate inputs, (ii) capital formation, and (iii) final use (consumption by households and governments).

and setting $\hat{C}_n = \frac{C'_n}{C_n}$ yields the expression for the change in welfare in the Proposition. ∎

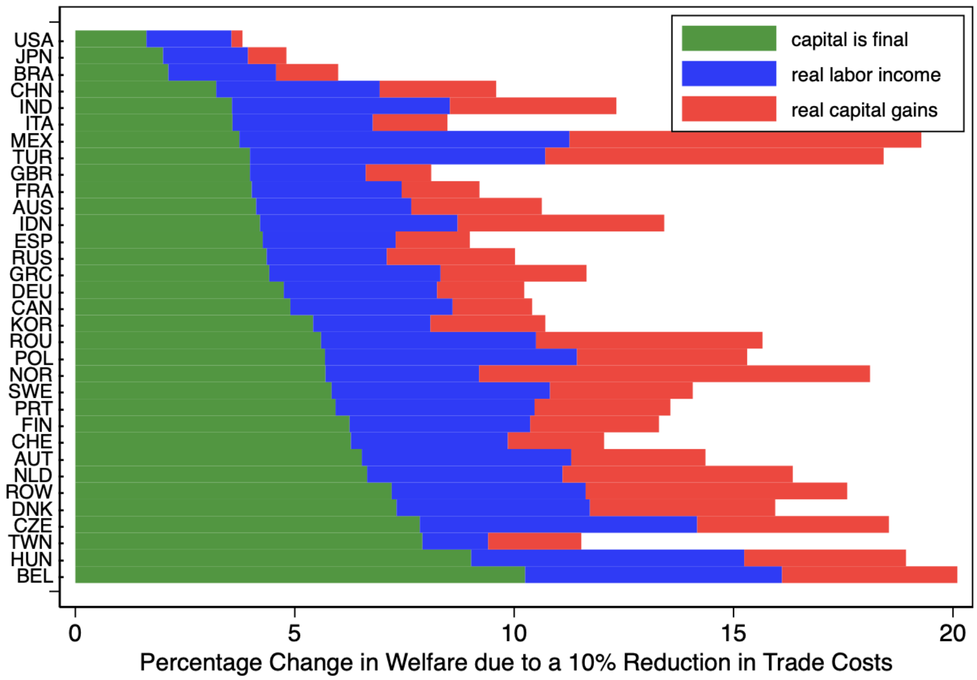
C Supplementary Figures and Tables

Figure C.2: Capital Shares of Output are Negatively Correlated with Intermediate Shares



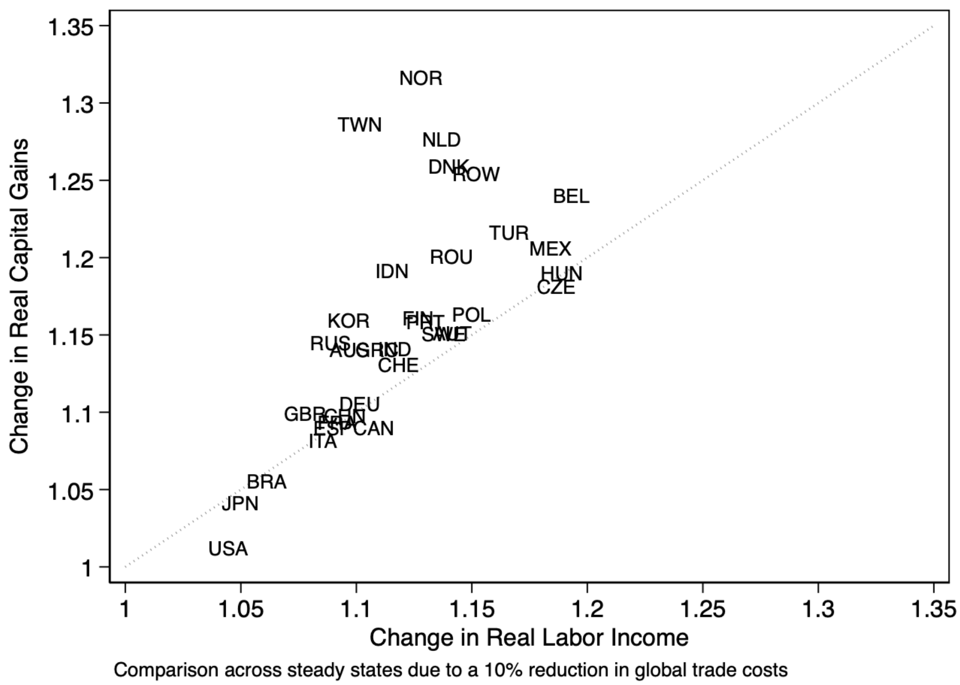
Notes: This figure compares a country's intermediate input cost-share of output against its capital services cost-share of output. The correlation is negative and statistically significant, with a simple regression t-statistic of -4.09.

Figure C.3: Decomposition of the Gains from Trade into Labor and Capital Gains



Notes: This figure extends the results displayed in Figure 2, which plots the per-period welfare gains from trade (in percentage terms: $100(\hat{C}_n - 1)$) in each country in the new global steady state of the economy due to a 10% reduction in trade costs across all country pairs $n \neq i$ in all industries. This figure decomposes the welfare gains in the model where capital services are intermediate inputs (orange bar in Figure 2) into two margins: the change in real labor income (here, in blue) and the change in real capital gains (here, in red), according to equation (12) in the paper.

Figure C.4: Trade liberalization-induced changes in real capital gains versus labor income



Notes: This figure compares the changes in the two sources of household consumption—labor income and capital gains—behind the 10% trade liberalization counterfactual considered in the paper. These are the blue and red bars in Figure C.3 divided by the pre-existing equilibrium share of income (s_n^L) due to labor versus capital ($1 - s_n^L$), respectively, so that what is plotted is the pure (unweighted) change in the two margins.