Capital Services in Global Value Chains

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Abstract

This paper constructs the first global dataset on inter-sectoral capital service flows. Capital assets are used in different relative proportions across sectors and countries. I use a dynamic general equilibrium model to quantify the importance of disaggregated capital in global production. Output prices in every country are sensitive to foreign shocks through a feedback loop between the cost of capital services and the cost of intermediate inputs. The per-period gains from trade in steady state are 8 to 36 percent higher than existing dynamic models and more than double that in static models. This amplification effect is higher in more capital-intensive countries. Under trade liberalization, output in each country reallocates towards sectors with the largest respective declines in capital service costs, disproportionately raising capital incomes. This mechanism in my model explains six percent of changes in sectoral market shares between 1997 and 2007.

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Under national-income accounting, some expenditures are expensed as intermediate inputs, whereas others are capitalized as investment. This choice bears real consequences for measurement of sectoral linkages. Researchers typically rely on input-output tables to identify the inputs used intensively by each sector. But standard input-output tables report only expenditures that are expensed. Equivalent input-output data on investment does not always exist, and even if it did, assumptions are needed to convert this data into per-period flows of capital services. This asymmetry in national-income accounting generates two challenges for researchers calibrating models to existing data. First, the accounting practice of capitalization leads to mismeasured sectoral linkages overall. Second, sectoral linkages are more prone to mismeasurement in countries that capitalize more input expenditures.

Given the prevalence of capital goods trade (Eaton and Kortum, 2001), this measurement issue is global in scale. Equipment, machinery, software and R&D all provide important capital service flows in global value chains. Take semiconductors for example. TSMC's production facilities in Taiwan use lithography machines imported from ASML in the Netherlands. Lithography production in turn uses optics components imported from Zeiss in Germany. A reduction in either German-Dutch or Dutch-Taiwan trade costs would propagate downstream to reduce the cost of Taiwanese semiconductors. And because semiconductors are typically expensed as intermediate inputs by other sectors (including machinery), any initial cost reduction would percolate across sectors and countries, amplifying the eventual consumer price benefit. But because Dutch machinery is imported into Taiwan as investment, existing data in world input-output tables do not identify the downstream sectors where these inputs are used.

Existing literatures have made different assumptions to circumvent the lack of disaggregated data on capital service flows. Models of global value chains and production networks (e.g., Antràs and Chor, 2022 and Acemoglu et al., 2012) focus on analyzing static sectoral linkages through adjustment in intermediate inputs but not investment and capital. A reduction in the price of imported machines would leave downstream production costs unchanged. On the other hand, multi-sector dynamic models (e.g., Burstein et al., 2008 and Johnson, 2014) treat capital as an aggregate composite good. Under this assumption, each sector uses different capital assets in the same relative proportions. A reduction in the price of imported machinery would counterfactually generate the same reduction in the cost of aggregate capital services for Taiwan's semiconductor sector as it would for Taiwan's education sector.

Instead, I tackle this data limitation head-on. I provide new data and theory to measure and quantify capital services in global production networks. I develop a multi-sector dynamic general equilibrium model where production requires a fully disaggregated set of sectoral intermediate inputs and capital services. Capital in my model is simply an intertemporal intermediate input (Hulten, 1979). A unit of invested capital today provides future flows of capital services that are eventually used up in production, consistent with Kuznets (1941)'s view that the only true final goods are household consumption at different time periods. And just like static intermediate inputs, a given type of capital service can be used more intensively in one sector than another.

My model provides a method to indirectly measure inter-sectoral expenditures on capital ser-

vices using data on new investment. Whenever investment is undertaken on a producer's own account, rental payment expenditures for capital services are non-market transactions and not directly observable. However, bilateral data on new investment (gross fixed capital formation) is reported in select national accounts and becoming increasingly available. My model provides equations linking the price of investment goods to the price of capital services, and the quantity of investment to the quantity of capital consumed. The first equation is the standard Jorgenson (1963) user cost formula. The second is the condition that investment exactly replenishes depreciated capital in steady state. Put together, the price and quantity equations allow me to identify expenditures on capital services from data on the value of new investment for every pair of supplying and using sectors.

I use this method to construct the first global input-output matrix of capital service coefficients. I hand-collect and harmonize data on inter-sectoral investment from over thirty countries and use the model's equilibrium condition to compute expenditures on capital services. To account for the fact that new investment might not equal capital service expenditures outside of steady state, I use only the *relative* information contained in the imputed capital service expenditures. I compute capital service coefficients—the elasticity of output in a sector to capital services supplied by another sector—by multiplying relative capital service expenditure shares into each sector's overall capital intensity. The capital input-output matrix provides disaggregated bilateral detail into the investment columns and capital value-added rows in standard world input output tables.[1] Put together, the capital-augmented world input output-table provides intermediate input coefficients as well as capital service coefficients at the same level of disaggregation.

This dataset reveals new facts on the global supply and use of capital services. First, I document heterogeneity. Comparable to intermediate input coefficients, capital service coefficients vary not only across countries (as shown in Caselli and Wilson, 2004) but also within a country across sectors. Construction capital is used intensively in healthcare whereas machinery is used intensively in manufacturing. These findings suggest underlying differences in sectoral production technologies and are inconsistent with the standard assumption that capital assets used in the same relative proportions in each sector. Second, inputs that are used more intensively as intermediates in a given sector and country are also used more intensively as capital, suggestive of considerable ambiguity in how accounting conventions are applied.

Third, I uncover a feedback loop between intermediate input producers and capital producers in global value chains. Sectors (like machinery) that use more imported-intermediate inputs tend to export a larger share of its output as investment, and sectors (like semiconductors) that use more imported capital services tend to export a larger share of its output as intermediates. Fourth, I show that reallocating investment expenditures away from final use and treating capital as an intertemporal intermediate input alters existing calculations of sectoral upstreamness. In my setting capital-supplying sectors are among the most upstream.

This specific configuration of capital in global value chains—heterogeneity, upstreamness, and

[1]Commonly used datasets include the World Input-Output Database (Timmer et al., 2015), the Inter-Country Input-Output (ICIO) Tables (OECD, 2022), and the Eora Global Supply Chain Database (Lenzen et al., 2012).

affinity with intermediate inputs—combine to generate stronger shock propagation than existing models calibrated to standard input-output data. The median elasticity of producer costs to foreign productivity shocks is 0.72. This is twelve times the direct effect (the median imported-input share of producer costs is 0.06), more than three times the effect when only accounting for the roundabout use of intermediate inputs (0.19), and still 22 percent higher compared to calibrations where capital service prices are endogenous but used by every sector in the same relative proportions.

Besides from measurement, I use my disaggregated-capital model for general equilibrium analysis. I revisit standard questions like the gains from trade where existing static and dynamic models have found different answers. Given capital's role as an intertemporal intermediate input, I use same equilibrium logic in static quantitative frameworks (Dekle et al., 2008; Caliendo and Parro, 2014) to solve for the exact impact of arbitrary shocks across steady states. In my model, combined sectoral input-output coefficients on intermediate inputs and capital services determine how shocks propagate across sectors. I show that the Leontief inverse of this capital-augmented input-output matrix enter as relevant parameters in a modified, long-run, "welfare gains from trade" formula in the spirit of Arkolakis et al. (2012).

My quantitative framework provides a common foundation to conduct model comparisons and assess the welfare impact of capital accumulation and capital heterogeneity. Because intermediate inputs and capital services enter symmetrically in production, my results are also insensitive to differences in accounting practices across countries. I compare results from my baseline, fully-disaggregated calibration to results from a benchmark static model and a benchmark dynamic model with aggregated capital. All three models are calibrated to match the same data in standard world input-output tables. In the static model calibration, capital service coefficients are set to zero, investment is part of final demand, and capital is a separate factor in fixed supply. In the aggregate-capital calibration, relative capital service coefficients in each country are equalized across sectors.

Disaggregating capital increases not only the propagation of country and sector-level shocks but also their aggregate impact. First, productivity shocks originating in capital-supplying sectors generate larger and more dispersed price impacts in other sectors, consistent with closed economy findings in Foerster et al. (2022). In an open economy with trade, productivity shocks that originate in a given country create winners as well as losers among other countries. There are two potentially-offsetting effects among other countries: a direct benefit through lower consumption prices, and an indirect general equilibrium effect through the terms of trade. Terms of trade improve for the shock-originating country and its input suppliers, but can be negative for output-competitors. Empirically, general equilibrium effects are strong enough to generate negative net cross-country elasticities of welfare to productivity for 40 percent of bilateral country-pairs. This result is unique to the disaggregated-capital calibration, suggesting capital adjustment in the *observed* production network generates sharp changes in comparative advantage and therefore the terms of trade.

Second, aggregate welfare gains from trade in my baseline model calibration are double those in the static calibration and 8 to 36 percent higher than the aggregate-capital calibration. Compared to the static calibration, increased gains from trade represent the contribution of capital accumulation.

On impact, trade liberalization lowers the prices of investment goods. When capital is allowed to adjust, competition in the market for capital services means prices must fall, which in turn lowers production costs and consumer prices downstream. Static models apply the same logic to how intermediate inputs adjust but ignore capital. Therefore the additional welfare gains are higher in more capital-intensive countries. Welfare gains in Mexico, which capitalizes 37 percent of its total expenditures, are 3.6 times higher than its static gains. Welfare gains in Korea, which capitalizes only 11 percent of its total expenditures, are only 1.5 times higher than its static gains.

Compared to the aggregate-capital calibration, additional gains from trade come from the specific configuration of capital in the global production network. I provide a quantitative decomposition to unpack the different mechanisms at work. I find that additional gains accrue mostly through higher incomes. Trade liberalization induces stronger changes in each country's comparative advantage when capital coefficients are heterogeneous. Rather than uniformly decreasing the prices of capital services across all sectors in a country, trade liberalization generates stronger declines in costs in some (imported-capital intensive) sectors compared to other (domestic-capital intensive) sectors. In every country, output reallocates towards its relatively more capital-intensive, export-oriented sectors where comparative advantage has grown, increasing capital incomes directly and overall income indirectly through in the terms of trade. I provide evidence consistent with this model-induced reallocation in the data. I apply the methodology in Head and Ries (2001) to extract the "revealed changes" in trade costs between 1997 to 2007, a period of rapid globalization. Holding fixed all other model primitives to their 1997 values, I find that these observed changes in trade costs alone explain six percent of the changes in sectoral market shares, compared to at most half that in calibrations without capital accumulation or capital heterogeneity.

Related Literature. The conceptual treatment of capital in my paper follows the literature on growth and national-income accounting. Early papers including Jorgenson and Griliches (1967), Hall (1968), and Hulten (1990) took on the challenge of measuring disaggregated capital and distinguished the aggregation of capital stock from the aggregation of capital service. The question of *which* expenditure outlays ought to count as investment under national income accounting is the subject of continued debate. Corrado et al. (2005) show that treating R&D as capital investment rather than an intermediate expense would increase GDP and lower labor's share of income, an argument echoed recently in Koh et al. (2020) and Barro (2021). My paper considers the consequences of capitalization not for national incomes but for sectoral linkages. Recent research in the real business cycle literature has started to highlight the importance of sectoral linkages through the supply and use of capital in the US economy. vom Lehn and Winberry (2021) construct an investment supply-use matrix and use it to explain aggregate correlations over the business cycle. Foerster et al. (2022) use similar data from the BEA's capital flow table to study the contribution of sectoral factors to long-run aggregate TFP growth.

Whereas this literature has been thus-far *national* in scope, I construct the first *global* dataset on the disaggregated flows of new investment and capital services across sectors and countries. This dataset fills a gap in our current understanding of the global supply and use of capital inputs, serves

as the natural counterpart to existing world input-output tables, and complements ongoing efforts by international statistical agencies to improve and coordinate accounting frameworks in light of global value chains (see e.g. Moulton and van de Ven, 2018 for efforts to account for multinationals and flows of intellectual property.)

My framework for measurement and new data contributes to the existing literature on global value chains, where both measurement and quantification has predominantly focused on *intermediate* input trade (e.g., Yi, 2003 Johnson and Noguera, 2012 and Antràs and Chor, 2013). My model disaggregates intermediates and capital services alike by the sectors of supply and use. This extension is natural considering that countries are rarely producers of the capital that they use (Eaton and Kortum, 2001). Embedding capital service flows in global value chains alters many empirical findings in this literature, leading to increased sectoral measures of upstreamness (relative to Antràs et al., 2012), increased GVC participation (relative to Hummels et al., 2001) and greater indirect exposure of producers to foreign shocks (similar to what Dhyne et al., 2020 document for Belgium).

My quantitative model is the dynamic analog of existing multi-sector models of trade (e.g., Caliendo and Parro, 2014 and Baqaee and Farhi, 2023), and their closed-economy cousins (e.g., Acemoglu et al., 2012 and Carvalho and Tahbaz-Salehi, 2019). These papers model capital as a fixed factor. Even in instances where capital is the subject of inquiry (e.g., Alvarez and Lucas, 2007 and Parro, 2013), the lack of supplementary data has necessitated calibrating the supply and use of capital from recorded intermediate-expense transactions in the standard input-output table. Instead, I model capital as an intertemporal intermediate input and calibrate its supply and use to new data on capital service flows. Despite the seemingly-expensive modification, equilibrium conditions in steady state inherit the same structure as these workhorse models. I show, however, that the welfare impact of trade liberalization and the productivity shocks more than double. These quantitative results resonate with parallel empirical research that have found imported capital to be an important driver of economic growth, including Wacziarg and Welch (2008) Cavallo and Landry (2010), Connolly and Yi (2015), and Lian et al. (2019).

In modeling investment and capital accumulation, my paper also relates to the literature on dynamic general equilibrium models of trade and their antecedents in the real business cycle literature (Long and Plosser, 1983; Horvath, 2000; Atalay, 2017). Numerous papers have sought to quantify the dynamic gains from trade. Some among them model capital as immobile (Alvarez, 2017) while others consider a single tradable sector (Boileau, 1999; Burstein et al., 2013; Anderson et al., 2020). Existing models featuring multiple sectors assume that each sector uses the same composite aggregate capital input (Kehoe et al., 2018; Mutreja et al., 2018; Ravikumar et al., 2019; Sposi et al., 2021; Bartelme et al., 2023; Huo et al., 2023). In this aggregate-capital setting any shock would generate the same change in cost of capital services in each sector.

I contribute to this literature by fully disaggregating capital supply and use across 41 countries and 27 sectors. The paper closest to my framework is Eaton et al. (2016), who employ a four-sector model with roundabout supply and use of intermediates and capital services to study the dynamics of the great trade collapse. However, they include only two capital-producing sectors (tradables

and construction) and ultimately calibrate capital coefficients to have, again, the same relative proportions in each sector and country. I show that heterogeneity is a quantitatively important feature of the global economy. In my disaggregated-capital setting, trade liberalization reallocates output in each country towards their respective sectors where costs have fallen the most. Changes in comparative advantage are stronger, and the increases in specialization generate welfare gains that are 8 to 36 percent higher than than existing dynamic calibrations.

The rest of the paper is organized around four sections. Section 1 elaborates on the current treatment of capital under national-income accounting and motivates the framework developed in this paper. Section 2 introduces the simple, neoclassical model that I use for measurement and analysis. Section 3 documents new empirical findings on the global capital input-output network, and Section 4 details results from quantitative analysis in general equilibrium.

1 Input Expenditure Accounting

This section illustrates how capitalization of input expenditures obfuscates measurement of the production network. Typical accounting conventions require expensing inputs that fully depreciate within a year. If inputs are expensed, they are entered as an "intermediate" transaction in national input-output tables, and the sectoral identities of the supplier and the user are provided. However, if capitalized, the supply of these inputs are entered as aggregate "investment" or gross fixed capital formation without specifying the using sector.

1.1 Capitalization of input expenditures obfuscates measurement

I begin with a stylized example. Consider a closed neoclassical economy with four sectors under perfect competition: (i) fishing rods, (ii) fishing, (iii) construction, and (iv) education. Fish and education are final goods consumed by households. Fishing rods and construction are inputs used to produce fish and education respectively. Each sector also uses labor as a primary factor input. There are $4L$ workers who supply their labor inelastically at a wage set as the numeraire. The economy is in steady state, workers are infinitely lived and near-infinitely patient, and the real interest rate is zero. Production technologies and preferences are such that L workers are employed in each sector.

Suppose that fishing rods last exactly a year, which creates ambiguity as to whether rods should be expensed or capitalized. Consider two versions of this economy that differ only in the accounting treatment of rod expenditures. The two panels of Table 1 provide representative input-output tables in each version and highlight differences in green. In version (A), expenditures L on rods by fish producers are recorded as an intermediate expense. In version (B), the same expenditures L are capitalized and recorded as investment, even though the fishing sector spends the same amount on new fishing rods each period (to replace depreciating rods). Implicit user costs (or rental payments) for the services of fishing rods show up as value-added by capital instead of an intermediate input expense. The single intermediate input flow of L in version (A) appears

Table 1: Example: standard input-output tables under different accounting conventions

Version (A)

Type of use (columns)	Intermediates				Investment	C	G.O.
Source of supply (rows):	Rods	Fish	Cnstr.	Educ.			
Rods		L					L
Fish						$2L$	$2L$
Construction					L		L
Education						$2L$	$2L$
Capital value-added				L			
Labor value-added	L	L	L	L			
Gross Output (G.O.)	L	$2L$	L	$2L$			

Version (B)

Type of use (columns)	Intermediates				Investment	C	G.O.
Source of supply (rows):	Rods	Fish	Cnstr.	Educ.			
Rods					L		L
Fish						$2L$	$2L$
Construction					L		L
Education						$2L$	$2L$
Capital value-added		L		L			
Labor value-added	L	L	L	L			
Gross Output (G.O.)	L	$2L$	L	$2L$			

Notes: C stands for final consumption by households and the government.

in two places in version (B): once as investment, and once again as value-added. All other cells (gross output, labor payments, and final consumption) remain the same. Both versions capitalize construction, the longer-lasting input, as investment.

The two versions of the economy are identical in economic terms and differ only due to the accounting treatment of rods. Both involve the same technologies, the same amount of workers, fishing rods, and construction used in each sector, the same amount of fish and education consumed per period, and thus the same household welfare. Yet differences in accounting conventions alone generate real consequences for measurement. The first difference is GDP. GDP is $5L$ in version (A) but $6L$ in version (B). Investment in fishing rods is "double-counted"—once in investment, and again in gross capital value-added.[2]

The second difference is measurement of sectoral linkages. In version (A), the cost share of fishing rods in the production of fish is 0.5. This cost share (along with the share of fish in final consumption, 0.5,) can be used to correctly infer that a one percent productivity shock in the rod industry would lower the prices of fish by 0.5 percent (and the consumption price index by 0.25 percent). However, this interdependence is absent in version (B). When expenditures on fishing

[2]Proponents of net capital accounting would argue that construction is also double counted in both versions, and a better measure of national income that corresponds to steady state household consumption should be $4L$ (see Kuznets, 1941; Weitzman, 1976; Barro, 2021).

rods are capitalized, a productivity shock in rods would appear to have no effect on the price of consumed fish. Even if the invested value of fishing rods were appropriately accounted for as final use (from being a part of GDP), the effect of a one percent productivity shock would lower the final price index by only one-sixth (its share in final use, now $C + I$) rather than by one-quarter of a percent (the correct amount).

Moreover, even if an analyst were to calibrate a dynamic model with capital accumulation, he would not be able to use data from version (B) to uncover the (true) cross-sector impacts of productivity shocks present in version (A). Here, mismeasurement takes on the form of not knowing which of the two downstream sectors (fishing or education) uses which type of capital (rods or construction). For example, under the often-invoked assumption that all downstream sectors use capital assets in the same relative proportions (i.e., through an "aggregate-capital" composite), a one percent productivity shock in the fishing rod sector would lower the price of aggregate capital services by 0.5 percent and therefore lower the price of fish by only 0.25 percent, half of its true value in version (A). The price of education would also be (incorrectly) predicted to fall by 0.25 percent whereas in version (A) it remains unchanged.

The example above reveals two problems with using conventional input-output data to calibrate multi-sector economic models of production. The first problem is obfuscation. Correctly predicting shock propagation in the long run requires disaggregating capital and linking the supplying sector to the using sector. Suppose every accountant operated under version (B). The supply-use of rods in fishing would be missing from standard input-output tables. For any input that is capitalized, additional information is needed on *where* it is ultimately used in order to correctly predict how a shock in one sector propagates to another. True sectoral linkages can differ dramatically from the standard "aggregate-capital" assumption that all sectors use capital assets in the same relative proportions.

The second problem is bias. In practice accounting conventions can differ systematically across countries, sectors, or time. Sectoral linkages would be more mismeasured under conventions that capitalize more inputs. This bias would apply to not only dynamic models (that use the aggregate-capital assumption) but also static models. Researchers who would rather ignore capital altogether (for example, if focusing on short-run impacts using a static model) still have to contend with the fact that some intermediate input expenditures can be recorded as investment (and vice versa).

1.2 Variation in input expenditure accounting

I show in Figure 1 that variation in input expenditure accounting manifests in the commonly-used World Input Output Database (WIOD). The database collects and harmonizes trade data and national input-output data from around 40 select countries in the world (Timmer et al., 2015).

Over the past two decades, changes to the international accounting guidelines under the System of National Accounts (SNA) have systematically reallocated bilateral industry flows away from intermediate expenses and towards investment. Most notably, the 1993 revision calls for capitalization of software expenditures and the 2008 revision calls for capitalization of R&D and

artistic original expenditures.[3] But this has been met with varying degrees of take-up across countries. For example, in the US National Income and Product Accounts (NIPAs), expenditures on software are not capitalized until 1999 and those on R&D and artistic originals not until 2013 (Bureau of Economic Analysis, 2019). Moreover, the SNA exists only as a guideline and there is no mechanism in place for enforcing strict adherence (Corrado et al., 2005).

Figure 1 panel (a) shows how this change in national accounting rules affects the share of R&D expenditures recorded as investment in the WIOD. In any given year, there is significant variation across countries in the share of R&D expenditures that are capitalized as investment. I divide WIOD countries into four groups based on their realized time path of R&D investment shares and use line thickness to visualize the relative size of each group. Countries in group 3 (including Portugal, Denmark, Greece, and others) consistently capitalize nearly all their R&D expenditures over the entire sample period, which could reflect efforts to backcast changes in accounting methodology to earlier releases of data. In comparison countries in group 1 (including the USA, Brazil, Canada, Japan, and others) on average capitalize only 24 percent of their R&D expenditures. The fact that this is again consistent over the entire sample period could reflect delays in updating their accounting methodology.

In comparison, for a large, compliant contingent of countries under group 2 (including the UK, Spain, Germany, France, Italy, Taiwan, Korea, and others), the share of R&D expenditures that are capitalized is near-zero before 2006 but steadily increases to near 90 percent by 2010. Two lone countries under group 4 (China and Australia) actually report a declining share of R&D expenditures that are capitalized, from 40 percent to near zero by 2006.[4] Given the lack of consistent accounting conventions across countries, any model calibrated to these input-output data would be biased, both across countries in any given time period (e.g., Portugal versus the UK in 2001) and across time in any given country (e.g., France in 2001 versus 2011).

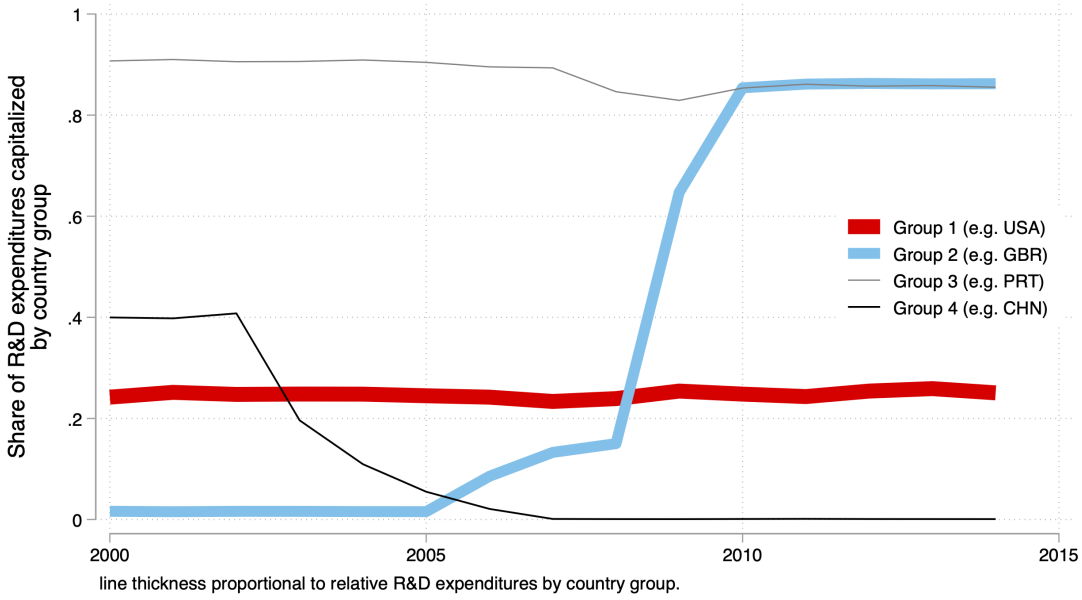
Next, in panel (b), I present evidence that this variation in accounting conventions exists not just for R&D; it occurs systematically across countries, time, and sectors in the WIOD database. I test whether producers in a given country, sector, and year that are more intermediate intensive tend to be less capital intensive. If accounting practices are indeed ambiguous, there would exist a negative correlation, as is the case in both the stylized example with fishing rods and in the real-world example with R&D. To ensure that R&D and related intellectual property products (IPPs) are not responsible for the correlation, this regression uses a prior release (in 2013) of the WIOD database when data was gathered before the group 2 set of countries had adopted the new accounting conventions. In this version of the dataset most IPP expenditures are consistently expensed over time (with the exception of a select few cases like Taiwan). I use this dataset as the

[3]See United Nations (1993) and United Nations (2009). 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 Table 1. See Koh et al. (2020) and Barro (2021) for more details and corresponding information on the BEA's treatment of software, R&D, and artistic originals.

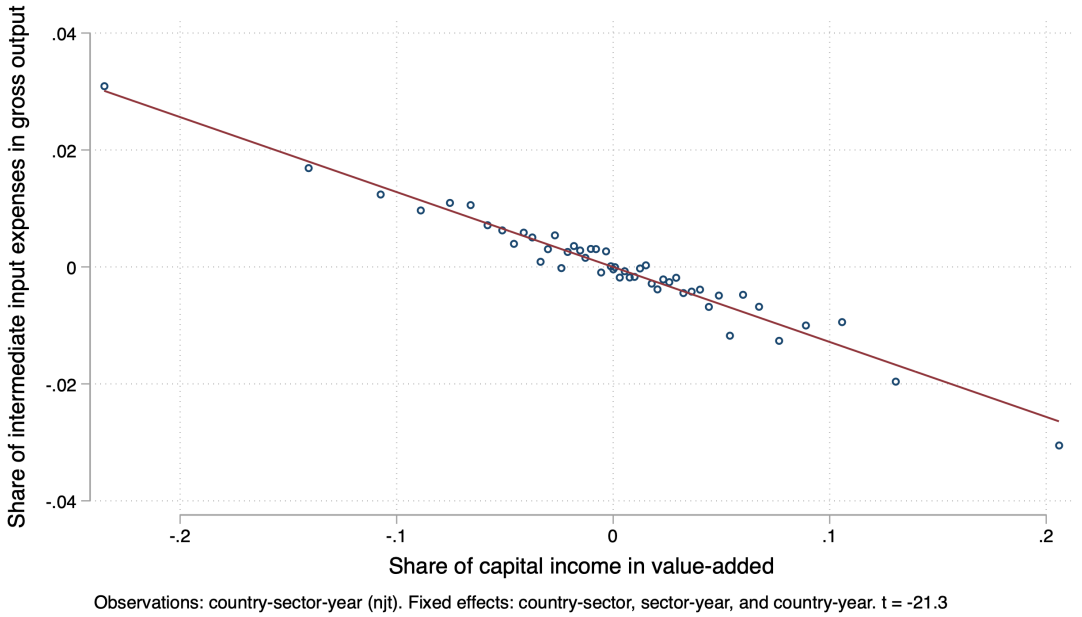
[4]These trends persist to this day and are not an artifact of WIOD methodology. In China, for example, only 26 percent of output supplied by the Research and Development and Technical Services sector is capitalized as investment, compared to 56 percent of output expensed as intermediates (National Bureau of Statistics of China, 2022).

Figure 1: Variation in Input Expenditure Accounting

(a) Specific Example: R&D Expenditure Accounting across Countries and Time



(b) Full Sample: Input Expenditure Accounting across Countries, Sectors, and Time



Notes: Panel (a) plots the annual share of total R&D expenditures that are capitalized as investment (as opposed to expensed as intermediates or consumed by households and government for final use) by four country groups. Countries are sorted into groups based on the time path of their R&D expenditure shares. Group 1 includes BRA, CAN, IDN, IND, JPN, MEX, RUS, TUR, USA. Group 2 includes AUT, BEL, DEU, ESP, FIN, FRA, GBR, HUN, ITA, KOR, NLD, NOR, POL, SWE, TWN. Group 3 includes CHE, CZE, DNK, GRC, PRT, ROU. Group 4 includes AUS and CHN. The R&D sector is coded as M72, "Scientific Research and Development" in the WIOD version 2016. Panel (b) plots a binscatter of the intermediate input share of gross output against the capital income share of value-added, by country-sector-year (njt), with nj, nt, and jt fixed effects.
Source: (a) WIOD, 2016 version, (b) WIOD, 2013 version with socioeconomic accounts.

baseline for analysis in the rest of the paper.

Panel (b) reveals a strong negative correlation between producers' intermediate input intensity in gross output and capital intensity in value-added.[5] Moreover, this correlation is robust to the inclusion of any combination of sector-year, country-sector, and country-year fixed effects, which control for many non-accounting related reasons why capital and intermediate intensity may differ. The negative correlation is statistically strong not only pooled but also separately (i) across countries for each sector-year, (ii) across years for each country-sector, and (iii) across sectors for each country-year.

This evidence is consistent with Corrado et al. (2005) who note the somewhat ambiguous durability cutoff in determining what becomes fixed investment. "The BEA's practice would appear to approximate a system in which business fixed assets are inputs with a useful service life of at least three years, although a dated study defines business equipment as having an average service life of more than one year" (p.31). Consistent with evidence in Figure 1, they also note that "different sectors in the NIPAs apply different accounting periods for capital." In addition to literal ambiguity in how accounting standards are applied, specific policies like investment tax subsidies (House et al., 2022) can also induce firms to capitalize rather than expense their expenditures.

2 Model of Capital Services in Global Value Chains

I develop a neoclassical multi-sector, multi-country dynamic general equilibrium model that overcomes the accounting-induced challenges of mismeasurement and bias. The model's sectoral production functions incorporate both disaggregated intermediate inputs and disaggregated capital services. I leverage the model's equilibrium conditions to apportion data on each sector's total capital value-added into specific capital service expenditures (equivalently, user costs or rental payments) broken out by each supplying sector and country. I use this method to construct the first global input-output matrix of capital service coefficients. The calibrated model is insensitive to variation in accounting conventions and permits quantitative analysis with little modification from existing quantitative benchmarks.

2.1 Model primitives

Let t denote time (in years), $n, i = 1, ..., N$ denote consuming and supplying countries, and $j, k = 1, ..., J$ denote consuming and supplying sectors respectively. The market structure is everywhere competitive. Within each sector j, varieties produced by each country i are traded and combined into a sector composite using a constant-returns CES function with elasticity of substitution $\theta_j + 1$ à la Armington. For simplicity, I assume there is no technological change,

[5] I compute the two shares using different denominators to prevent the correlation from being mechanically negative (which can occur if labor intensity, capital intensity, and intermediate input intensity measured in terms of gross output are all random). The intermediate input share is computed by dividing expenditures by gross output and the capital share is computed by dividing by total value-added (sum of labor and capital payments). The t-stat is stronger (at -40) if I use gross output as the denominator in both measures.

no economic uncertainty, and perfect foresight. In this paper I focus only on characterizing the model's steady-state, leaving transition dynamics to future research.

Consumption. The representative household in each country n has standard inter-temporal preferences with discount factor $\rho < 1$ and concave utility $u(.)$:

$$U_n = \sum_{t=0}^{\infty} \rho^t u(C_{nt}),$$

where final consumption $C_{nt} \equiv \prod_j C_{njt}^{\alpha_{nj}}$ is a Cobb-Douglas function over sector composites C_{njt} with country-specific preference parameters $\sum_j \alpha_{nj} = 1$.

Production. The model features roundabout production. The CES-composite output in each sector can be used either as inputs by the same sector, by another sector, or as part of final consumption (by households or governments). If expensed, inputs enter as intermediates m in the production function. If capitalized, they provide per-period service flows κ in the production function. I assume that production functions are everywhere Cobb-Douglas:

$$q_{ijt} = A_{ijt} \cdot l_{ijt}^{\beta_{ij}^L} \prod_{k=1}^{J} m_{ijkt}^{\beta_{ijk}^M} \prod_{k=1}^{J} \kappa_{ijkt}^{\beta_{ijk}^K}, \tag{1}$$

where q_{ijt} is country i's variety of output in sector j, A_{ijt} is TFP, and $\beta_{ij}^L, \beta_{ijk}^M, \beta_{ijk}^K$ are production coefficients representing the elasticity of output with respect to labor, intermediate inputs from sector k, and capital services from sector k. Production coefficients satisfy $\beta_{ij}^L + \sum_{k=1}^{J} \left(\beta_{ijk}^M + \beta_{ijk}^K\right) = 1$ (constant returns to scale) and can vary across countries and sectors.

Investment and Capital Accumulation. Households have access to a riskless savings technology in units of the final good. In steady state $C_{nt} = C_{n,t-1}$ and the household Euler condition pins down the interest rate r^f on a one-period bond (in zero net supply) as $1 + r^f = \rho^{-1}$.

Households can invest in goods supplied by any sector k and install them as capital in any sector j to provide a stream of rental service flows over time.[6] Each unit of capital provides a unit of service flow. Capital stocks κ_{jkt} are specific to both the supplying and using sectors (e.g. computers k supplied for use in healthcare j), depreciate at supplying-sector-specific rate δ_k and are replenished by new investment I_{ijkt} according to:

$$\kappa_{ijk,t+1} = (1 - \delta_k)\kappa_{ijkt} + I_{ijkt}. \tag{2}$$

A no-arbitrage condition pins down the rental price of capital services (r_{ijkt}) in steady state. The net present asset value of a unit of capital supplied by k and installed in j at the start of a

[6] Assuming that households make investments and then rent out their per-period capital services to firms is equivalent to assuming that firms make capital investments by borrowing from households at the required rate of return.

period t, V_{ijkt}, is equal to the price of capital services r_{ijkt} plus its discounted value next period net of depreciation:[7]

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

Asset values and prices are constant in steady state, so that $V_{ijkt} = V_{ijk,t+1}$. Given my focus on the steady state, I drop the t subscript in what follows. Under no-arbitrage, the return on a one-period bond $(1 + r^f)$ equals the return on investing in any good k (at purchase price P_{ik}), so that

$$1 + r^f = \frac{V_{ijk}}{P_{ik}} = \frac{r_{ijk}}{P_{ik}(1 - \frac{1}{1+r^f}(1 - \delta_k))},$$

which relates the rental price of capital services (r_{ijk}, or Jorgenson, 1963's user cost of capital) to the price of the initial investment good (P_{ik}):

$$r_{ijk} = P_{ik}\left(r^f + \delta_k\right). \tag{3}$$

Trade. The CES consumption price index for the sectoral composite j in each country n is:

$$P_{nj} = \left(\sum_i (\tau_{nij} c_{ij})^{-\theta_j}\right)^{-\frac{1}{\theta_j}}, \tag{4}$$

where τ_{nij} denotes bilateral iceberg trade frictions between importer n and exporter i, and c_{ij} denotes the unit cost of production in country i in sector j, which, using equation (3) to replace r_{ijk} with P_{ik}, can be expressed as:

$$c_{ij} = A_{ij}^{-1} w_i^{\beta_{ij}^L} \prod_k P_{ik}^{\beta_{ijk}^M + \beta_{ijk}^K} \eta_{ij}, \tag{5}$$

where the constant η_{ij} contains production coefficients β, depreciation rates δ, and the interest rate r^f. Lastly, import shares take on the constant-elasticity form:

$$\pi_{nij} = \frac{(\tau_{nij} c_{ij})^{-\theta_j}}{\sum_{i'} (\tau_{ni'j} c_{i'j})^{-\theta_j}}, \tag{6}$$

and do not vary by type of use, consistent with assumptions made in the WIOD.

Equation (5) delivers a key insight for how shocks in one sector affect unit costs in another. Any shock that changes prices in upstream sector k affects downstream sector j both through sector j's use of intermediate inputs from k (β_{ijk}^M) as well as its use of capital from k (β_{ijk}^K). Sector propagation is therefore determined by *capital-augmented* "input-output" coefficients $\beta_{ijk}^M + \beta_{ijk}^K$. Under this symmetric treatment of intermediate inputs and capital services, calibration of sectoral linkages is insensitive to differences in accounting conventions.

[7] I assume that capital assets of a given type k depreciate at the same rate δ_k regardless of sector j of use. It is trivial to allow depreciation in the model to depend on both k and j, though data requirements would be heftier.

2.2 Global equilibrium in steady state

I assume that each country operates under financial autarky. All expenditures (including investment) are funded by households from the purchasing country. I model trade deficits (D_n) as exogenous net transfers across countries. While I do not focus on the closed-economy setting in this paper, it should be clear that my model nests it with $\tau_{nij} = \infty$ (or, more trivially, by specifying just one country). Appendix B.1 contains some derivations under autarky to help convey intuition.

In steady state, capital stocks are constant and investment exactly replenishes depreciation, $I_{ijk} = \delta_k K_{ijk}$. I combine this quantity relationship with the price relationship (equation 3) to link the value of new investment $P_{ik}I_{ijk}$ to expenditures on capital services $r_{ik}\kappa_{ijk}$:

$$P_{ik}I_{ijk} = \frac{\delta_k}{r^f + \delta_k} r_{ik}\kappa_{ijk} = \frac{\delta_k}{r^f + \delta_k} \beta^K_{ijk} X_{ij}, \tag{7}$$

where the second equality imposes market clearing for capital services.

Equation (7) reveals that only a fraction of gross capital income from each asset k is re-invested in steady-state. The remaining fraction $\frac{r^f}{r^f+\delta_k}$ is net capital income and spent on final consumption goods as compensation to households for investments made in the past. Accordingly, the more patient are households, the lower is the required rate of return $1 + r^f$, and the lower is net capital income.[8]

Definition 1 uses equation (7) to condense the solution for the steady state in terms of labor market and goods market clearing conditions alone. Goods markets clear when gross output X_{ij} in each sector is exhausted by consumption from each importing country n across the three types of use: (i) as intermediates, (ii) as investment, and (iii) as final consumption. I use bold math notation to denote variables in matrix or vector form.

Definition 1 (Global Steady State) *Given labor $\boldsymbol{L}$, consumption coefficients $\boldsymbol{\alpha}$, production coefficients $\boldsymbol{\beta}$, TFP shifters $\boldsymbol{A}$, interest rate r^f, depreciation rates $\boldsymbol{\delta}$, trade imbalances $\boldsymbol{D}$, iceberg trade costs $\boldsymbol{\tau}$, and trade elasticities $\boldsymbol{\theta}$, the solution to the global steady state can be expressed in terms of output $\boldsymbol{X}$ and relative wages $\boldsymbol{w}$ that satisfy:*

1. *Labor market clearing in each country i: $w_i L_i = \sum_j \beta^L_{ij} X_{ij}$,*
2. *Goods market clearing in each sector j in each country i:*

$$X_{ij} = \sum_n \pi_{nij} \left[\sum_k \left(\beta^M_{nkj} + \frac{\delta_j}{r^f_n + \delta_j} \beta^K_{nkj} \right) X_{nk} + \alpha_{nj} \left(w_n L_n + D_n + \sum_j \sum_k \frac{r^f_n}{r^f_n + \delta_j} \beta^K_{nkj} X_{nk} \right) \right],$$

where import shares $\boldsymbol{\pi}$ from equation (6) are a function of $\boldsymbol{w}$ and other model primitives using equations (4) and (5).

[8] The fishing example in Table 1 corresponds to the limiting case where $r^f \to 0$ and therefore no capital income is used for consumption and there is full double-counting of investment.

My model features three key differences compared to static and dynamic quantitative trade models. First, compared to static model calibrations, there is greater circularity in production in the model's steady state. Input-output coefficients reflect the use of not only intermediate inputs (β^M_{ijk}) but also capital services (β^K_{ijk}), amplifying the impact of a cost shock in any investment-supplying sector k on downstream capital-using sectors j.

Second, the fully disaggregated production network differs from benchmark dynamic multi-sector models of trade that treat capital as an aggregate. In a typical aggregate-capital framework, assets from different sectors k are purchased in the same proportions to form the composite capital, which is then used in all sectors j. Relative capital service intensities across k are invariant between two using sectors j and j'; in other words, $\frac{\beta^K_{jk}}{\sum_k \beta^K_{jk}} = \frac{\beta^K_{j'k}}{\sum_k \beta^K_{j'k}}$ for all j and j'.

A final difference with both static and dynamic models lies in how output and factor incomes adjust in response to shocks. Both labor and (net) capital incomes are used for final consumption and their relative proportions are endogenous to trade-induced reallocations of output. As trade liberalization lowers the price of capital services through the price of imported investment (relative to labor), each country shifts its output towards its mix of imported-capital-intensive industries where comparative advantage and export demand has risen. This mechanism can increase total consumption income as well as capital's share of income relative to labor in each country.

3 Measurement and Facts on the Capital Input-Output Network

In this section I exploit the model's steady-state relationship between gross fixed capital formation and capital service expenditures to measure the global capital input-output network: the dependence of output in sector j in country n on capital supplied by sector k in country i. I use this data to document and quantify new sources of interdependence in the global economy.

3.1 Constructing the capital-augmented global input-output table

My primary data source is the WIOD. This dataset provides the annual sales of any origin country i and sector k to any destination country n for use as either (i) intermediate inputs in a sector j, (ii) gross fixed capital formation, (iii) final consumption by households and the government. The data cover the years 1995 to 2011 and feature 41 economic regions (including a rest-of-the-world aggregate). I supplement these data with the WIOD's socioeconomic accounts, which break out value-added into labor compensation and other (capital) income by sector by country.

The unshaded cells in Table 2 correspond to data available from the WIOD. For ease of exposition, I suppress the cross-country dimension in this example. These values allow for the conventional calibration of preference coefficients, $\boldsymbol{\alpha}$, bilateral intermediate input coefficients, $\boldsymbol{\beta}^M$, labor coefficients, $\boldsymbol{\beta}^L$, and aggregate capital coefficients, β^K.

However, bilateral capital service coefficients (β^K_{ijk}) are impossible to calibrate from WIOD data alone. There are two types of bilateral data missing from this conventional input-output table. First, the cells in green constitute the investment matrix, where aggregate investment expenditures

Table 2: Example: two-sector capital-augmented input-output table

Type of Use (columns):	Intermediates		Investment (GFCF)			C	G.O.
Source of Supply (rows):	by j	by k	Total	(by j)	(by k)		
Intermediate inputs:				Bilateral GFCF:			
from j	$\beta^M_{jj}X_j$	$\beta^M_{kj}X_k$	$\frac{\delta_j\left(\beta^K_{jj}X_j+\beta^K_{kj}X_k\right)}{r^f+\delta_j}$	$\frac{\delta_j}{r^f+\delta_j}\beta^K_{jj}X_j$	$\frac{\delta_j}{r^f+\delta_j}\beta^K_{kj}X_k$	$\alpha_j S$	X_j
from k	$\beta^M_{jk}X_j$	$\beta^M_{kk}X_k$	$\frac{\delta_k\left(\beta^K_{jk}X_j+\beta^K_{kk}X_k\right)}{r^f+\delta_k}$	$\frac{\delta_k}{r^f+\delta_k}\beta^K_{jk}X_j$	$\frac{\delta_k}{r^f+\delta_k}\beta^K_{kk}X_k$	$\alpha_k S$	X_k
Capital value-added: (= sum of capital services)	$\beta^K_j X_j$	$\beta^K_k X_k$					
from capital supplied by j	$\beta^K_{jj}X_j$	$\beta^K_{kj}X_k$					
from capital supplied by k	$\beta^K_{jk}X_j$	$\beta^K_{kk}X_k$					
Labor value-added	$\beta^L_j X_j$	$\beta^L X_k$					
Gross Output (G.O.)	X_j	X_k					

Notes: C stands for final consumption by households and the government. The set of unhighlighted cells represent the data available in a standard input-output table. Highlighted cells represent additional measurement on capital input-output relationships undertaken in this paper. Highlighted cells in green are often reported as bilateral GFCF. Highlighted cells in yellow are imputed rental payments on capital services by input-output sector pair.

on each supplying row-sector are broken out across using column-sectors. Second, the cells shaded in yellow constitute the capital services matrix, where aggregate capital expenditures by each using column-sector are broken out by across supplying row-sectors.[9]

Direct measurement of the capital service matrix (cells in yellow) would be difficult even with perfect data because these expenditures are often borne as internal user costs and are not transactions at arms length. However, the investment network (cells in green) is increasingly provided as part of national accounts under "bilateral gross fixed capital formation (GFCF)", albeit often at a more aggregated level of detail.

I develop an algorithm that first constructs a disaggregated global investment matrix containing $P_{ik}I_{ijk}$. Then I leverage equation (7) to infer capital service expenditures ($r_{ik}\kappa_{ijk}$) in the equilibrium of the model as a function of observed investment $P_{ik}I_{ijk}$. An advantage of this measurement strategy is that it requires only contemporaneous data on transacted *values* and is thus free of the additional assumptions needed to compute separate measures of quantities and prices by capital asset by vintage, for example under the perpetual inventory method. I describe the algorithm and data sources in full in Appendix A.2 and summarize it briefly below.

Step 1. To construct the investment matrix, I use shares ω_{njk} to apportion the WIOD's unilateral GFCF by asset k $P_{n,k}I_{n,k}$ across using sectors $j \in \mathcal{K}$ in each destination country n:

$$P_{nk}I_{njk} = P_{nk}I_{nk}\omega_{njk} \qquad \forall n, j, k,$$

[9]Given the neoclassical assumptions in the model, the the aggregate value of capital services is equivalent to gross operating surplus and to total value-added less labor compensation.

where apportioning shares satisfy $\sum_j \omega_{n,jk} = 1 \; \forall k$. To construct ω_{njk}, I use a combination of (i) hand-collected bilateral GFCF data from country-specific national accounts for thirty out of forty countries in the WIOD sample and (ii) the aid of model-implied shares in instances where bilateral detail is too aggregated and for the ten countries where bilateral GFCF data does not exist. For the U.S. and Mexico, bilateral GFCF data is available at a more aggregated level than $\mathcal{K}$ so the shares ω_{njk} can be computed directly as the share of all investment in k made by sector j. For each remaining country where bilateral GFCF data is more aggregated than $\mathcal{K}$, I first construct aggregated apportioning shares at the exact level of detail reported for that country, and then sub-apportion investments according to using sectors $j \in \mathcal{K}$ assuming that the country uses capital services of various assets k *within* each more aggregated asset class in the same proportions as the U.S. In short, I use as much country-specific disaggregated detail as available from its respective national accounts, before turning to the model's predictions for bilateral GFCF in steady-state.

Step 2. Armed with the global investment matrix $P_{nk}I_{njk}$, I use equation (7) to directly compute rental payments on capital services (rK, the cells highlighted in yellow). However, taking these imputed rental payments at face value may generate total value-added by capital that either exceeds or falls short of the aggregate row in the standard input-output table. This can occur whenever the global economy is not in steady state. Investments made today reflect expectations of future economic conditions, so for growing sectors investments may exceed the depreciation on capital and for shrinking sectors investments may fall short. I therefore use only information on *relative* rental payments contained in equation (7) to compute *relative* rental payment shares γ^K_{njk} across asset-supplying sectors k for each given using sector j. I then use these relative shares γ^K_{njk} to apportion overall capital share of gross output (β^K_{nj}, available in the WIOD) into specific bilateral capital coefficients k:

$$\beta^K_{njk} = \gamma^K_{njk}\,\beta^K_{nj}, \quad \text{where} \quad \gamma^K_{njk} = \frac{P_{nk}I_{njk}\frac{r^f+\delta_k}{\delta_k}}{\sum_{k'} P_{n,k'}I_{njk'}\frac{r^f+\delta_{nk'}}{\delta_{k'}}}, \qquad \forall n, j, k.$$

Besides from direct values of new investment, depreciation rates $\boldsymbol{\delta}$ and the risk-free rate r^f also influence capital coefficients. The factor $\frac{r^f+\delta_k}{\delta_k}$ adjusts for the fact that between two capital assets k and k' with the same observed equilibrium values of GFCF, the asset with the lower-depreciation rate commands a higher rental service income to compensate impatient investors for a longer payback schedule. This is another potential source of mismeasurement of sectoral linkages. Typical model calibrations that do not allow for asset-specific depreciation rates overstate the importance of traded, fast-depreciating assets relative to often non-traded, slow-depreciating assets. The higher is the risk-free rate, the greater is the premium commanded by the lower-depreciation sector. I set the risk-free rate r^f equal to 0.03 in all countries, and I use the BEA's estimates of depreciation rates by asset type k to calibrate $\boldsymbol{\delta}$.

Step 3. Finally, I apportion njk-level investments and capital service expenditures to various supplying countries i using import shares π_{nik} taken from the WIOD. This is consistent with the standard assumption that import shares do not differ by type of use (final demand, investment, or intermediates by using-sector j.

3.2 New facts on capital services in global production

Figure 2 visualizes the input-output matrix of capital service coefficients, β^K_{njk}, summed over origin countries i for four select using-countries n in the year 1997. Panels (a) and (b) visualize coefficients for the USA and Mexico, for which fully disaggregated bilateral GFCF data exist. Panels (c) and (d) visualize coefficients for Japan and Korea, for which apportioning investment at the bilateral level require combining more aggregated bilateral data with assumptions from the theory. Most of the capital services used in production in each country are provided by a handful of sectors: construction, machinery, electrical equipment, transport equipment, professional services and wholesale, retail, transportation, repair.

Because capital service coefficients are computed on a relative basis (using shares γ^K_{njk} apportioned into β^K_{nj} in step 2 of the algorithm), the capital input-output table is consistent with overall capital intensities in the WIOD. Korea is the least capital-intensive country ($\beta^K_{KOR} = 0.11$) and Mexico is the most capital-intensive country ($\beta^K_{MEX} = 0.37$). Correspondingly, Korea has the sparsest capital input-output matrix and Mexico has the densest. To the extent that differences in capital intensities are caused by differences in accounting practices, combined coefficients $\beta^M_{njk} + \beta^K_{njk}$ put the two countries on more equal footing (the combined $\beta^M_{njk} + \beta^K_{njk}$ difference between Korea and Mexico halves to 0.13). I return to this comparison in the quantitative analysis in Section 4.

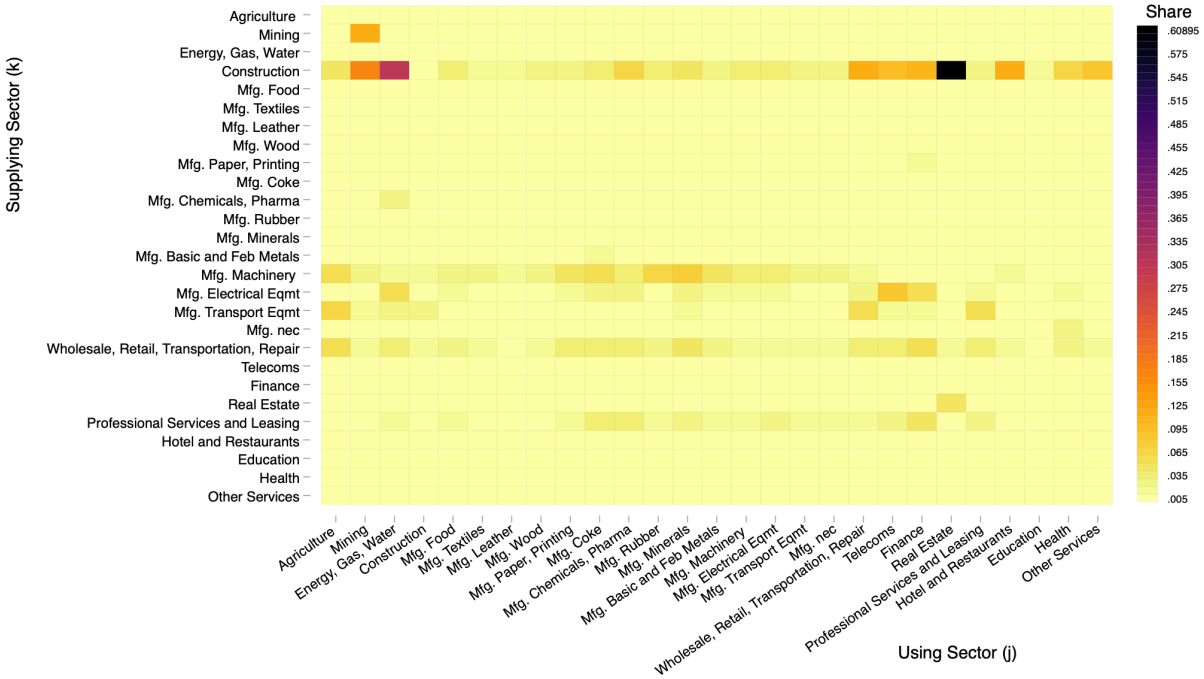
I use this newly-assembled capital input-output network to document five empirical findings on the role of capital in global production.

Empirical Finding 1: Heterogeneity in relative capital asset use. Figure 2 reveals that the capital services of assets k are used in differing proportions across sectors j and countries n. For example, in the US, hotels, restaurants, and healthcare services use mostly construction capital, whereas manufacturing uses more machinery and equipment capital. For any given sector, this dependence also varies across countries. For example, among manufacturing producers, machinery and equipment capital is relatively more important for US producers but construction and transportation and repair are relatively more important for Mexican producers. Suppliers from the from the professional services sector (which provides R&D, software, and other IPP) do not sell their output as investment in Mexico and Korea but do so in the US and Japan (to producers from the finance, telecoms, and pharmaceuticals sectors). These findings are inconsistent with the assumption in dynamic models that capital assets are used in the same relative proportions.

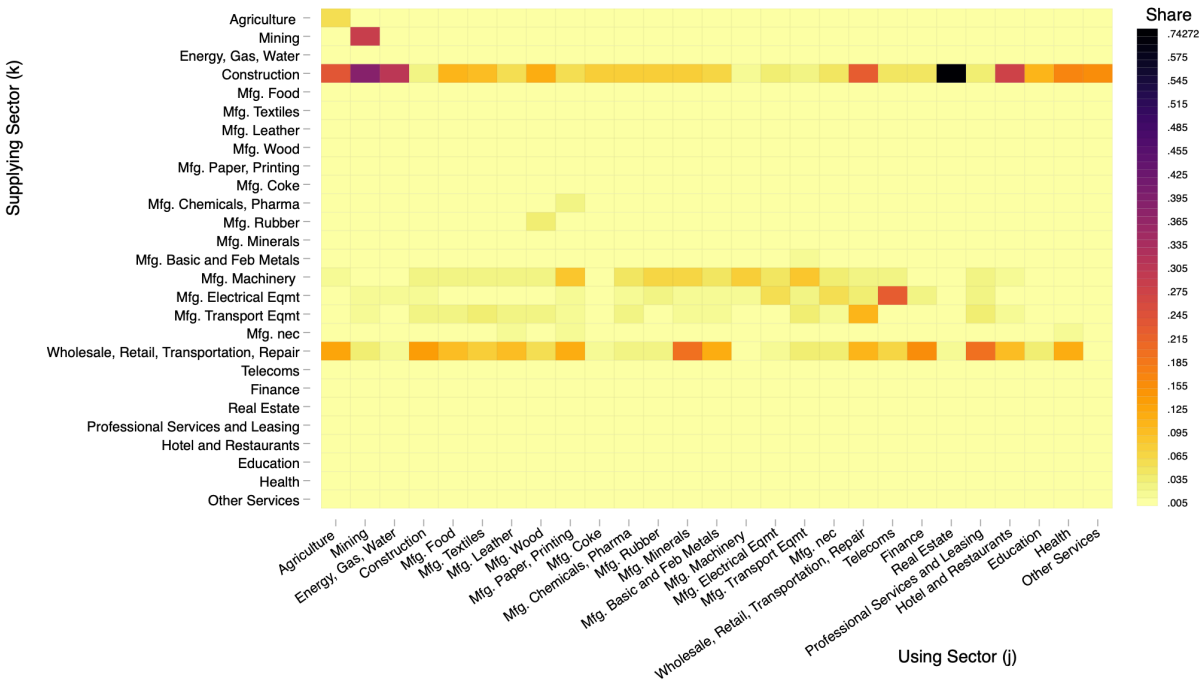
I formalize these observations in Table 3. I find that the standard deviation in capital coefficients is systematically higher than that in intermediate coefficients in the entire cross-section. To make the comparisons fair I report results using normalized coefficients γ^K and γ^M that sum to one

Figure 2: Input-output matrix of capital service coefficients, β^K_{njk} for select countries in 1997:

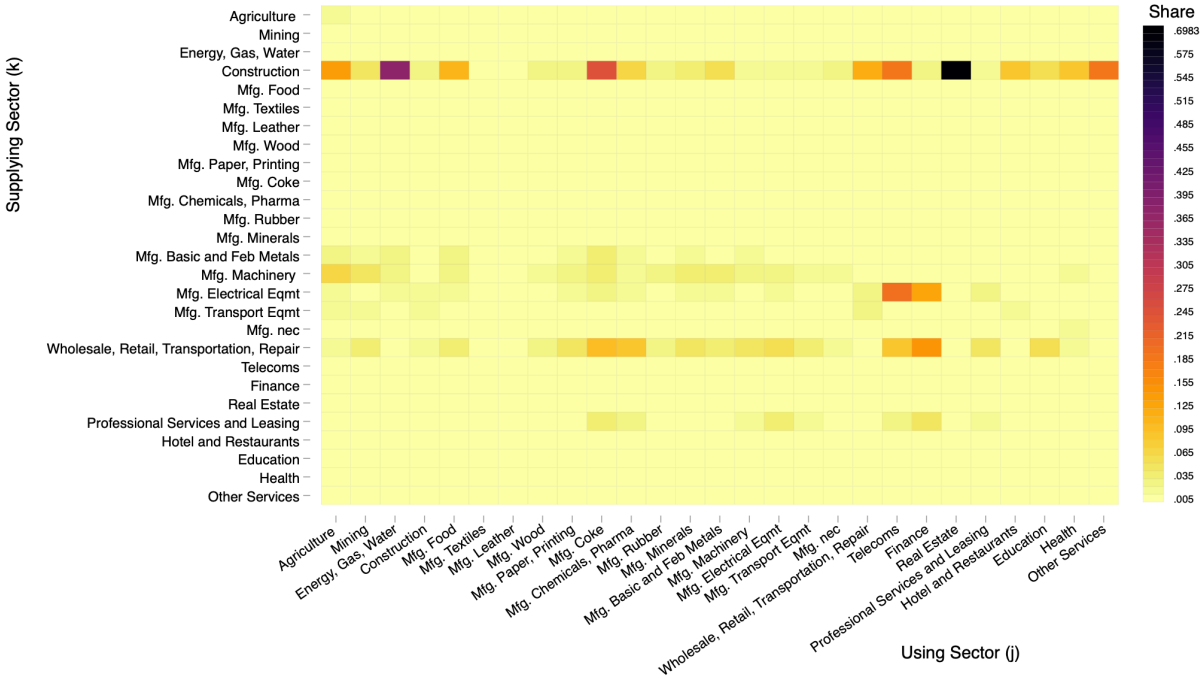
(a) USA



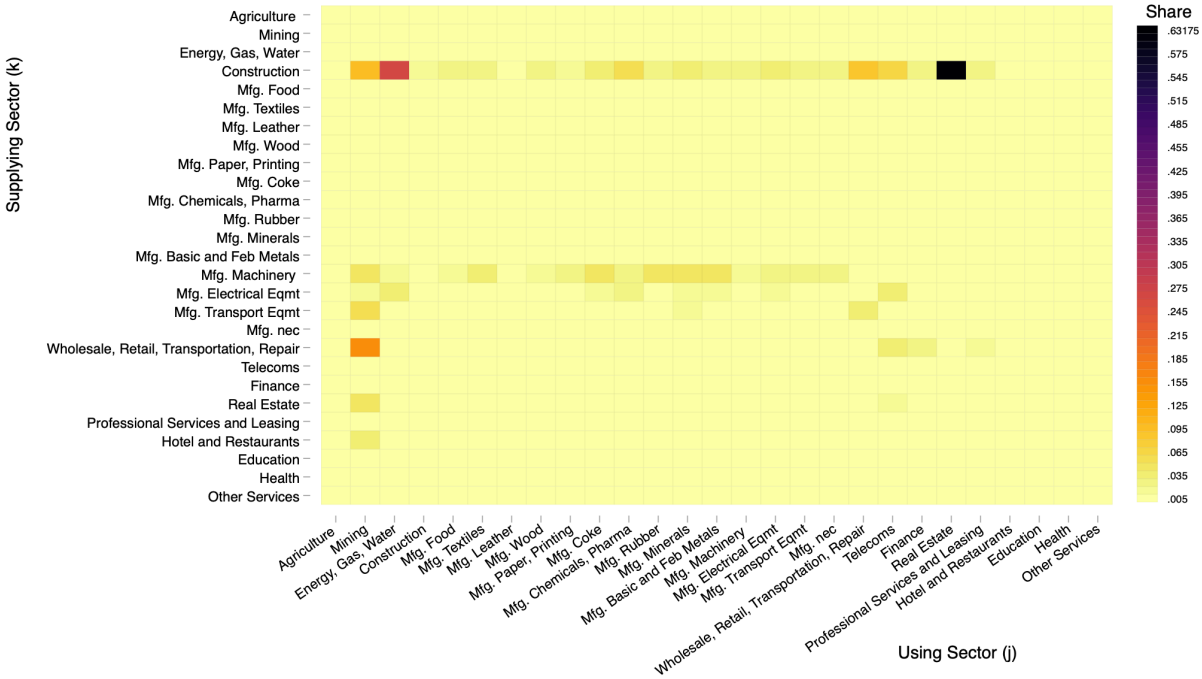
(b) Mexico



(c) Japan



(d) Korea



Notes: This figure visualizes the input-output matrix of capital service coefficients for four select countries: (a) USA, (b) Mexico, (c) Japan, (d) Korea. Each cell corresponds to β^K_{njk}: the expenditures $r_{njk}\kappa_{njk}$ by the using sector j on capital services from capitalized investment goods supplied by sector k as a share of the using sector's gross output X_j.
Source: WIOD (w/ socioeconomic accounts), plus bilateral GFCF from OECD and select national accounts in 1997, plus author's calculations.

Table 3: Heterogeneity in use of intermediate inputs and capital services

RMSE in:	Share of nj expenditures capitalized (K) and expensed (M) paid to sector k	
	γ^K_{njk}	γ^M_{njk}
Controls:		
(i) none	0.110	0.076
(ii) nk fixed effects	0.057	0.069
(iii) jk fixed effects	0.049	0.038
(iv) nk and jk fixed effects	0.039	0.036

Note: This table computes the root mean squared error of normalized capital and intermediate coefficients (γ^K_{njk}, γ^M_{njk}) before and after residualization on various fixed effects. 29,889 observations (27 supplying sectors k, 27 using sectors j, 41 using countries n). *Source:* 1997 WIOD w/ socioeconomic accounts, national accounts, and author's calculations.

within each using country-sector nj pair. Row (i) reports the raw standard deviations without any controls. The subsequent rows residualize the coefficients on fixed effects by (ii) country-supplying sector nk (to focus on variation across using sectors j), (iii) supplying-using sectors jk (to focus on variation across countries n), and (iv) both.[10] Capital coefficients are more dispersed than their intermediate input counterparts both in the raw data, across countries n for every jk pair, and after controlling for both sets of fixed effects. In comparison, under the "aggregate-capital" assumption that each sector j in a country n uses capital assets in the same relative proportions, variation in γ^K_{njk} would be zero in the second and fourth rows.

Empirical Finding 2: Capital-Intermediates affinity in production. Figure 3 reveals that country-sectors that use inputs from sector k more intensively as intermediates tend to also use inputs from sector k more intensively as capital. The statistically significant relationship between γ^K_{njk} and γ^M_{njk} is, again, robust to inclusion of any subset of input-output sector, country-output sector, and country-input sector fixed effects. The t-statistic on the most conservative specification—with all three bilateral fixed effects—is 3.24. This finding suggests that the augmented input-output coefficients $\beta^K_{njk} + \beta^M_{njk}$ would deepen more than disperse existing cross-sector (and cross-country) value chains. Sectors that were already supplying output for use as intermediate inputs also supply output for investment, amplifying their importance for shock propagation.

These results are also consistent with the accounting ambiguity documented across sectors and countries in Figure 1. For a given country-sector (nj), if an input k is technologically more useful for production, it is likely to be used more intensively both as an intermediate and as capital precisely when accounting standards are ambiguous.[11]

Empirical Finding 3: Capital-intermediate feedback loop in GVCs. Figure 4 documents a positive correlation between a country-sector's output-based and input-based measures of GVC

[10] The nj dimension is omitted because the normalized shares are constructed to sum to 1 for each nj.

[11] I also check that the positive affinity between a given input k's use as capital and its use as an intermediate in Figure 3 is not driven that fact that some sectors' output are mechanically never used as either intermediates or capital. Removing the 17 percent of njk triplets that have either $\beta^M_{njk} = 0$ or $\beta^K_{njk} = 0$ actually increases the t-stat (to 3.43).

Figure 3: Capital-Intermediates affinity in production, 1997



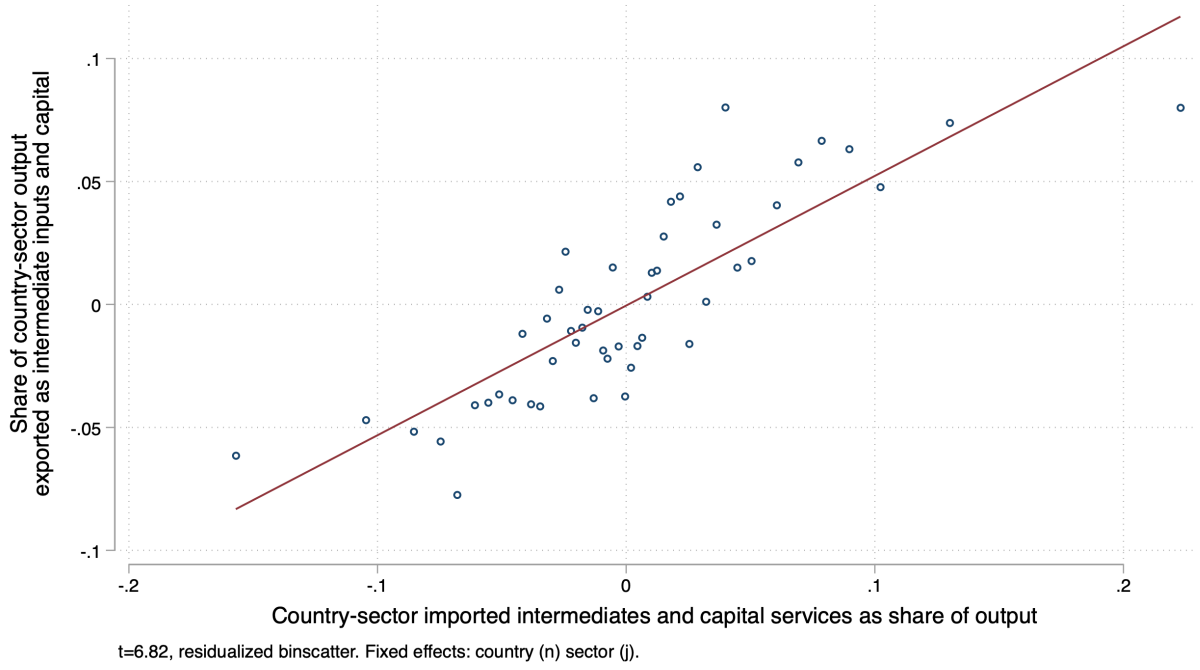
Notes: This figure plots, for each producer country-sector nj and input sector k triplet, the share of nj's total rental payments made for the capital services of sector k, against, on the x axis, the share of nj's total intermediate expenses paid to inputs from k.
Source: WIOD w/ socioeconomic accounts, national accounts, and author's calculations.

participation. I compute output-based GVC participation as the share of each country-sector nj's gross output exported as intermediates or investment, and input-based GVC participation as the share of its total expenditures (gross output) paid to both imported intermediates and capital services:

$$\sum_{i \neq n} \sum_{k} \pi_{nik} \left(\beta^{M}_{njk} + \beta^{K}_{njk} \right).$$

Input-output associativity in GVC participation implies that lower imported input prices for any given producer are not simply absorbed in the importing country (in final demand) but also propagated to indirect buyers in third countries. Table 4 goes further to decompose the association between overall imported-input use and overall exported-output supply into the contribution of intermediate inputs versus capital. The first two columns reveal that the inclusion of capital services strengthens the positive correlation between imported inputs and exported output (documented in Hummels et al., 2001). The remaining columns reveal a feedback loop between intermediates and capital services in GVCs. Producers intensive at exporting capital services intensively use imported intermediate inputs, and producers intensive at exporting intermediate inputs intensively use imported capital services. This is consistent with the example in the introduction: ASML exports semi-conductor manufacturing machinery to TSMC but imports lens from Reiss, whereas TSMC imports semi-conductor machinery but exports chips.

Figure 4: Input-output associativity in GVC participation



Notes: This figure plots, for each producer country-sector nj the share of total output exported as capital against, in the x axis, imported expenditures on intermediates and capital services as a share of total output.
Source: 1997 WIOD w/ socioeconomic accounts, national accounts, and author's calculations.

Table 4: Input-output homophily in GVCs

Share of output exported as:	M and I	M	M	M	I	I	I
Cost share of imported M and K	0.53***						
$\sum_{i\neq n}\sum_k \pi_{nik}\left(\beta^M_{njk}+\beta^K_{njk}\right)$	(0.08)						
Cost share of imported M		0.43***		0.46***	0.11***		0.10***
$\sum_{i\neq n}\sum_k \pi_{nik}\beta^M_{njk}$		(0.08)		(0.07)	(0.03)		(0.03)
Cost share of imported K			0.22	0.39***		-0.09*	-0.05
$\sum_{i\neq n}\sum_k \pi_{nik}\beta^K_{njk}$			(0.15)	(0.15)		(0.04)	(0.05)
Country n fixed effects	Y	Y	Y	Y	Y	Y	Y
Sector j fixed effects	Y	Y	Y	Y	Y	Y	Y
N	1,105	1,105	1,105	1,105	1,105	1,105	1,105
R^2	0.69	0.64	0.62	0.64	0.69	0.68	0.69

Note: M stands for intermediate inputs, K for capital services, and I for investment. Robust standard errors in parentheses.
*** p<.01, ** p<.05, * p<.1
Source: 1997 WIOD w/ socioeconomic accounts, national accounts, and author's calculations.

Empirical Finding 4: Capital-supplying sectors are more upstream. The capital-augmented input-output table allows researchers to link downstream sectors that use capital rental services to the upstream sectors that initially supplied the capital as investment. "Upstreamness" in my long-run economic framework differs from static-based approaches taken up by Antràs et al. (2012). In their calculations, investment is treated as 'final use' along with household and government consumption. Investment-supplying sectors therefore count among the most downstream.

However, capital in my framework is equivalent to an intertemporal intermediate input. From a long-run economic point of view, it is reasonable to expect shocks to investment-supplying sectors to propagate to other downstream producers. Given increased depreciation and obsolescence rates for capital (e.g., from efforts to capitalize intellectual property products, a growing category of investment), shocks to capital-supplying sectors can also propagate downstream in the near-to-medium term.

I therefore provide an alternative measure of a sector's relative position in the global value chain. My measure reflects the use of both intermediates and capital services from the input dimension, and the supply of both intermediates and investment from the output dimension. Given the previous empirical finding that these two sides of GVC participation are positively correlated, I compute my measure in an open economy context using the full capital-augmented input-output coefficients, $\boldsymbol{\beta}^M + \boldsymbol{\beta}^K$.

Using the goods market clearing condition in Definition 1, total sectoral output can be split into output sold for downstream producer use (as intermediates or capital) and for final demand:

$$X_{ij} = \underbrace{\sum_n \sum_k \pi_{nij} \left(\beta^M_{nkj} + \frac{\delta_j}{r^f_n + \delta_j} \beta^K_{nkj} \right) X_{nk}}_{\text{producer use}} + \underbrace{F_{ij}}_{\text{final demand}},$$

which can be expressed in matrix notation succinctly as

$$\boldsymbol{X} = \tilde{\boldsymbol{B}}\boldsymbol{X} + \boldsymbol{F},$$

where $\boldsymbol{X}$ and $\boldsymbol{F}$ are $NJ \times 1$ vectors and $\tilde{\boldsymbol{B}}$ is a $NJ \times NJ$ matrix with elements ik per row and jn per column equal to $\pi_{nij} \left(\beta^M_{nkj} + \frac{\delta_j}{r^f_n + \delta_j} \beta^K_{nkj} \right)$.

I define upstreamness U_{ik} in country i sector k as the weighted-average number of times its output is sold before absorption by final demand:

$$U_{ik} = \frac{\tilde{U}_{ik}}{X_{ik}}, \tag{8}$$

where the numerator can be computed as

$$\tilde{\boldsymbol{U}} \equiv \boldsymbol{I}\boldsymbol{F} + 2\tilde{\boldsymbol{B}}\boldsymbol{F} + 3\tilde{\boldsymbol{B}}\boldsymbol{F} + 4... = [\boldsymbol{I} - \tilde{\boldsymbol{B}}]^{-2}\boldsymbol{F} = [\boldsymbol{I} - \tilde{\boldsymbol{B}}]^{-1}\boldsymbol{X}.$$

This measure essentially adjusts the Antràs et al. (2012) measure of upstreamness by reallocating all final use purchased as investment as part of producer (i.e., 'intermediate') use and extending measurement to an open economy setting.[12]

Figure 5 displays upstreamness calculations under the conventional measure (in blue) and the capital-augmented measure (in red). Panel (a) presents the average upstreamness by sector (across all countries) and panel (b) the average upstreamness by country (across all sectors). Every sector is weakly more upstream under the capital-augmented measure. This is not surprising because every producer now sells weakly less output to what is considered final demand.

More notably, sectors that experience the largest increases in upstreamness are capital-supplying sectors like construction, transport equipment, machinery, and electrical equipment. Other already-upstream sectors like minerals, mining, basic and fabricated metals that supply intermediate inputs to capital-producing sectors also see large gains in upstreamness. Accordingly, sectors that see the least increase in upstreamness are healthcare, education, and food manufacturing because these sectors primarily sell to final households and the government rather than other producers.

Panel (b) reveals smaller but still notable differences across countries. The average good produced in China is sold 3.5 times before it reaches final demand, whereas the average good produced in Cyprus and Greece is sold less than 2 times before it reaches final demand. These findings indicate that countries differ in their GVC positioning and therefore differ in how they transmit shocks abroad via the production network.

Empirical Finding 5: Increased sensitivity to foreign shocks. Finally, I illustrate that accounting for the supply and use of capital in production amplifies the sensitivity of producer costs to foreign shocks. For any producer in sector j in country n, the 'direct' effect of a shock to all foreign prices (such as to technology A_{ik} $\forall i \neq n, \forall k$) can be computed from equations (4) and (5) as:

$$\mathrm{d}\log c_{nj} = \sum_k \pi_{nij} \left(\beta^M_{njk} + \beta^K_{njk}\right) \mathrm{d}\log A_{ik}, \qquad \forall i \neq n, \forall k. \tag{9}$$

However, this direct effect misses the fact that with roundabout production both domestic suppliers and (yet other) foreign suppliers would in turn experience lower input costs themselves, *ad infinitum*. Log-differentiating and combining equations (4) and (5) yields an expression linking the full elasticity of producer costs $\boldsymbol{c}$ (a NJ vector) to foreign shocks (either productivity $\boldsymbol{A}$ or trade costs $\boldsymbol{T}$):

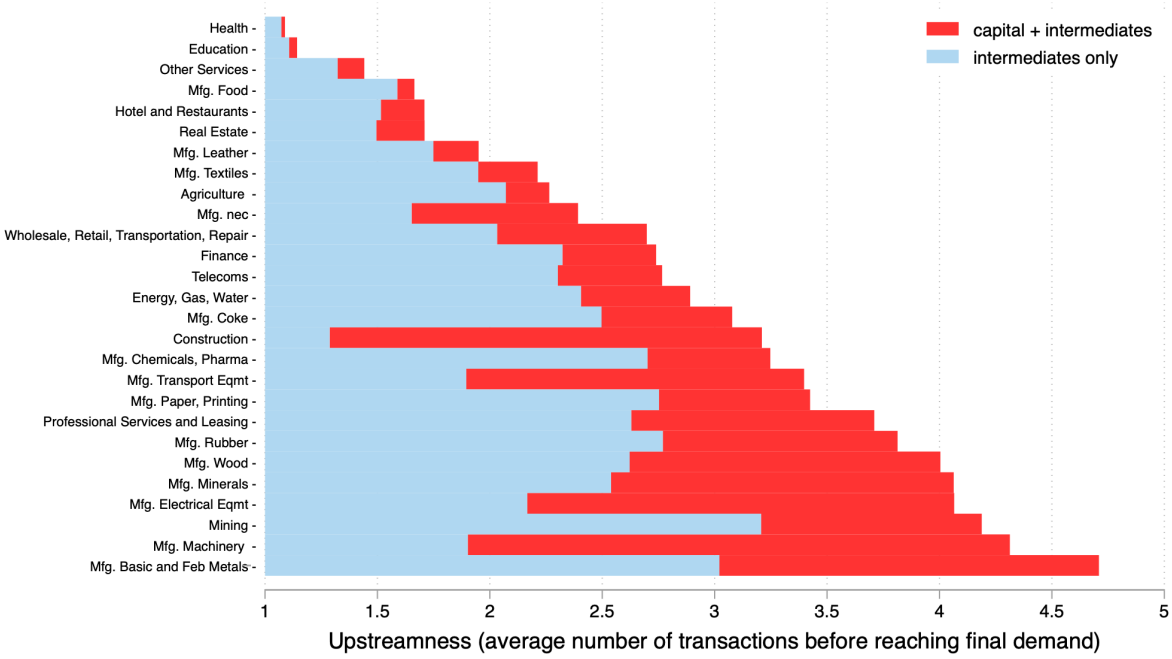
$$\mathrm{d}\log \boldsymbol{c} = [\boldsymbol{I} - \boldsymbol{B}]^{-1} \left(-\mathrm{d}\log \boldsymbol{A} + \mathrm{d}\log \boldsymbol{T}\right), \tag{10}$$

where $\boldsymbol{B}$ is a matrix with elements in row (i, j), column (n, k) given by augmented imported-input-output coefficients $B_{ij} \equiv \pi_{ink}(\beta^M_{ijk} + \beta^K_{ijk})$, and $\mathrm{d}\log \boldsymbol{T}$ is a NJ vector of imported-input-weighted

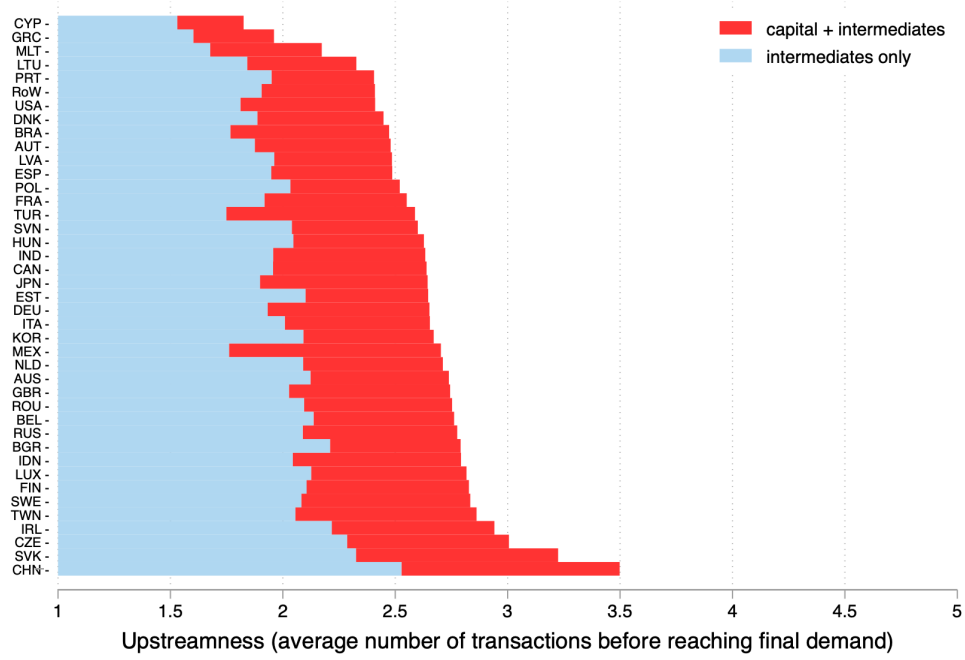
[12] One advantage of the WIOD-based data compared to using domestic I/O tables alone is that I can trace production and consumption exactly as it occurs across the globe rather than assume how output of a given sector is used whenever it is exported abroad.

Figure 5: Capital-Augmented Measures of Upstreamness

(a) Average Upstreamness across Sectors

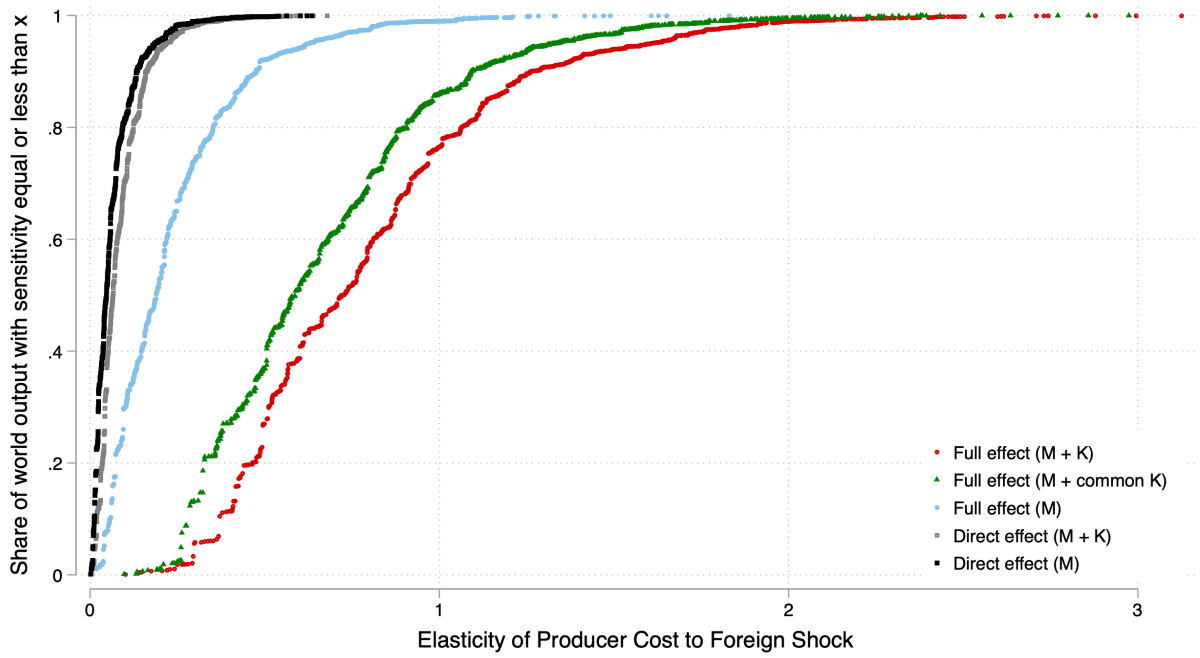


(b) Average Upstreamness across Countries



Notes: This figure plots, for each producer country-sector nj, the measure of upstreamness in equation (8) averaged using value-added as weights (a) over countries to the sector-level and (b) over sectors to the country level.
Source: 1997 WIOD w/ socioeconomic accounts, select national accounts, and author's calculations.

Figure 6: Distribution of Producer Cost Elasticity to Foreign Productivity Shocks



Notes: This figure plots the cumulative distribution of the producer cost elasticity to a uniform foreign productivity shock for each country-sector pair (n, j) in the augmented WIOD data in 1997. Shown are the elasticities computed under five different scenarios: (i) in red, the full effect as in equation (10) using capital-augmented input-output coefficients, (ii) in green, the full effect as in equation (10) using capital-augmented input-output coefficients that assume common relative capital service intensities across all sectors, (iii) in blue, the full effect as in equation (10) using conventional intermediate input-output coefficients, (iv) in grey, the direct effect as in equation (9) using capital-augmented input-output coefficients, (v) in black, the direct effect as in equation (9) using conventional intermediate input-output coefficients.
Source: 1997 WIOD w/ socioeconomic accounts, national accounts, and author's calculations.

shocks to trade costs given by elements $\mathrm{d}\log T_{ij} \equiv \sum_k \sum_n \pi_{ink} \left(\beta^M_{ijk} + \beta^K_{ijk}\right) \mathrm{d}\log \tau_{ink}$.

Figure 6 illustrates the global distribution of the elasticity of producer costs to foreign productivity shocks and demonstrates the disproportionate participation of capital users and producers in global value chains. For each country-sector n, j, I repeatedly compute the expression in equation (10) by setting $\mathrm{d}\log A_{ik} = 1$ for all k and all foreign countries $i \neq n$. I plot the cumulative distribution (over all country-sectors n, j) of this full elasticity incorporating intermediates (M) and capital services (K) in the red scatter. For comparison, the blue scatter displays the cost elasticity distribution under the conventional recognition of only intermediate inputs M in production linkages (when $\boldsymbol{B}$ contains only conventional imported-input-output coefficients $\pi_{ink}\beta^M_{ijk}$).

Moving from the conventional intermediates-only calibration to the capital-augmented calibration causes domestic cost-elasticities to be higher both for the average sector and for a wider swath of sectors. The red line is shifted everywhere to the right, indicating that at every percentile of global output shock propagation is amplified. In the conventional intermediates-only

scenario (in blue), only 20 percent of global output has a cost-elasticity larger than 0.35. In the capital-augmented scenario (in red), 84 percent of global output has a cost-elasticity larger than 0.35, suggesting the effects of foreign shocks become more common when the supply and use of capital (much of which require imported inputs or is itself imported) is taken into consideration. Amplification is largest around the median of the distribution: the median dollar sold in the world has a producer cost elasticity to foreign shocks of 0.72 under the capital-augmented scenario compared to 0.19 when considering intermediates only, more than a three-fold increase.

Part of this amplification comes from the exact input-output configuration of global value chains rather than the (more obvious) change to make capital service prices endogenous. The green scatter computes the cost-elasticity distribution when the model is calibrated allowing for capital accumulation but under the standard assumption that capital is a composite formed out of the consumption good and used in equal relative proportions everywhere.[13] In this model, sectors have the exact same capital intensities and match the same conventional input-output table. But the cost-elasticities computed using the same equation (10) fall short of the disaggregated distribution in red. The median dollar sold in the world has a producer cost elasticity to foreign shocks of 0.59 under this common-capital scenario. Knowledge of the disaggregated capital input-output network increases the cost-elasticity by 22 percent for the median dollar, demonstrating that knowledge of the precise network generates shock transmission that differs not just at the bilateral sectoral level (the more obvious example, with fish and fishing rods), but even in the aggregate.

Finally, the grey and black lines show for comparison the cost-elasticity distribution is much lower when considering only the *direct* impact of reduced foreign input prices. The grey scatter plots the distribution when intermediates and capital services are taken into consideration, whereas the black scatter shows the conventional intermediates-only case. The median producer only has six percent of its costs accruing to directly imported intermediates and capital. The black and grey distributions are also barely discernable from one another, indicating that production is on average more much more intermediates-intensive than capital-intensive (the two have similar import shares in the data). Comparing these distributions to the full-effect distributions suggests that capital plays a large role in the *indirect* propagation of economic shocks. For example, as the prior three findings indicate, capital producers are themselves intermediates intensive and their output is in turn used intensively by intermediates-producing sectors.

One limitation of using equation (10) to evaluate changes in the global economy is that it serves as only a local approximation. The approximation could be poor if shocks were large enough to affect wages, or large enough to change import shares given the CES-demand structure. It may also seem unfair to allow capital rental prices to adjust (implicitly, comparing changes in the steady-state under market clearing in all capital services) without allowing for wages to adjust under labor market clearing. In the next section I conduct general equilibrium counterfactuals and show that all these insights of amplification and dispersion persist.

[13] I set $\beta^K_{njk} = \alpha_{nk}\beta^K_{nj}$, where α are final-use shares taken out of C+I+G in the conventional input-output table and β^K_{nj} is the observed capital-value-added as a share of gross output common to both calibrations.

4 Quantifying the Impact of Capital Services in Global Value Chains

In this section I use the hat algebra framework popularized by Dekle et al. (2008) to solve for exact changes across steady states given arbitrary shocks. Under the capital-augmented production network, productivity shocks generate larger and more dispersed impacts on prices across sectors and countries. Trade liberalization generates larger welfare gains from trade compared to both static models (the intermediates-only scenario) as well as dynamic models where capital is modeled as an aggregate. Finally, I put these various model calibrations to the test and show that the capital-augmented input-output network explains the most observed reallocation in country-sector-level output in the data.

4.1 Solving for the impact of shocks across steady states

Proposition 1 solves for the exact impact of arbitrary shocks to model fundamentals (technology, population, trade frictions, or imbalances) on the global steady state. Changes in equilibrium variables and the exogenous shocks are expressed in hat changes, where $\hat{y} \equiv \frac{y'}{y}$ denotes the value of any variable y' in the new steady state relative to its value y in the old steady state. An advantage of Proposition 1 is that the initial values $\{\boldsymbol{\pi}, \boldsymbol{wL}, \boldsymbol{D}\}$ and model parameters $\boldsymbol{\beta}, \boldsymbol{\alpha}, \boldsymbol{\delta}, r^f, \boldsymbol{\theta}$ can be easily calibrated to data from the capital-augmented input-output table.

Proposition 1 (Counterfactuals in the Global Steady State) *Let there be unanticipated, exogenous shocks to trade costs $\{\hat{\tau}_{nij}\}_{n,i,j}$, population size $\{\hat{L}_{ij}\}_{i,j}$, TFP $\{\hat{A}_{ij}\}_{i,j}$, and/or imbalances $\{\hat{D}_n\}_n$. Using the model parameters $\boldsymbol{\beta}, \boldsymbol{\alpha}, \boldsymbol{\delta}, r^f, \boldsymbol{\theta}$ and initial equilibrium data on import shares $\boldsymbol{\pi}$, labor income $\boldsymbol{wL}$, trade imbalances $\boldsymbol{D}$ alone, the solution to the new steady state of the global economy can be expressed in terms of exact changes in wages $\{\hat{w}_n\}_n$ such that:*

1. *The labor market clears in each country i: $\hat{w}_i \hat{L}_i w_i L_i = \sum_k \beta^L_{ik} X'_{ik}$,*

2. *Goods markets clear in each sector 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:*

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

4. *Changes in unit costs of production in each country i in sector 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:*

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

Besides from changes in sector-level prices given above, I also examine changes in country-level welfare. I define welfare as per-period real income used for consumption. The change in welfare $\hat{C}_n$ is thus the share-weighted average of the change in real labor income and the change in real net capital income (the portion of gross capital income not used to cover depreciation):[14]

$$\begin{aligned} \hat{C}_n &= \frac{\hat{w}_n \hat{L}_n w_n L_n + \sum_j \sum_k \frac{r_n^f}{r_n^f + \delta_j} \beta_{nkj}^K X'_{nk}}{w_n L_n + \sum_j \sum_k \frac{r_n^f}{r_n^f + \delta_j} \beta_{nkj}^K X_{nk}} \prod_k \hat{P}_{nk}^{-\alpha_{nk}} \\ &= s_n^L \cdot \underbrace{\frac{\hat{w}_n \hat{L}_n}{\prod_k \hat{P}_{nk}^{\alpha_{nk}}}}_{\Delta\text{real labor income}} + (1 - s_n^L) \cdot \underbrace{\frac{\sum_k \mu_{nk} \hat{X}_{nk}}{\prod_k \hat{P}_{nk}^{\alpha_{nk}}}}_{\Delta\text{real net capital income}}, \end{aligned} \tag{11}$$

where μ_{nk} and s_n^L are shares that denote country n's share of net capital income from sector k, and country n's share of total final consumption out of labor income:

$$\mu_{nk} \equiv \frac{\sum_j \beta_{nkj}^K \frac{r^f}{r^f + \delta_j} X_{nk}}{\sum_{k'} \sum_j \beta_{nk'j}^K \frac{r^f}{r^f + \delta_j} X_{nk'}}, \qquad s_n^L \equiv \frac{w_n L_n}{w_n L_n + \sum_j \sum_k \frac{r_n^f}{r_n^f + \delta_j} \beta_{nkj}^K X_{nk}}.$$

Given the definition of welfare in equation (11), Corollary 1 extends the formula for the gains from international trade in Arkolakis et al. (2012) to incorporate capital accumulation in a setting with multiple sectors and input-output linkages.

[14] Under the model's values of δ and r^f, roughly 20 percent of consumption expenditures are financed from net capital income in the initial steady state. Results do not quantitatively change when using the change in real GDP as a proxy for welfare in lieu of the change in real consumption income. I include deficits (exogenous transfers D_n) in market clearing conditions but ignore deficits in the interpretation of welfare because it is not clear that deficits are used to fund household expenditures. Including deficit spending in the definition of welfare matters little in practice because deficits are constant across counterfactuals and a small share of total consumption expenditures.

Corollary 1 (Gains from International Trade) *The gains from international trade in country n are:*

$$GFT_n \equiv 1 - \frac{C_n^{autarky}}{C_n} = 1 - \prod_{j,k} \pi_{nnk}^{\frac{\tilde{\beta}_{njk}\alpha_{nj}}{\theta_j}} \left(1 + (1 - s_n^L)(\hat{R}_n - 1)\right), \tag{12}$$

where $\tilde{\beta}_{njk}$ are elements of the Leontief inverse matrix of combined input-output coefficients $\beta_{njk}^M + \beta_{njk}^K$, s_n^L is the share of labor income in total consumption income given by equation (11) and $\hat{R}_n \equiv \sum_k \mu_{nk}\hat{X}_{nk}$ is the change in net capital income computable from Proposition 1 by setting $\hat{\tau}_{nik} = \infty$ for all $n \neq i$, removing imbalances $\hat{D}_n D_n = 0$, and choosing $\hat{w}_n = 1$ as the numeraire.

There are two modifications compared to the standard gains from trade formula under multiple sectors and input-output linkages provided by Costinot and Rodríguez-Clare (2014). First, the Leontief inverse takes into account both capital and intermediate input-output coefficients. This increases the degree of roundaboutness in production (since capital is allowed to adjust) and increases the gains from trade. Second, the term in parentheses accounts for changes in relative capital incomes (wages w_n are set as the numeraire). Although the adjustment implies that trade shares alone are no longer sufficient statistics for the gains from trade, I show in Appendix C.3 that $\hat{R}$ is easily computable as a matrix inverse of known parameters and expenditures in the initial equilibrium. Compared to Proposition 1 which solves for arbitrary counterfactuals, one advantage of the GFT formula is that autarky counterfactuals for a country n requires only data on domestic input-output coefficients, depreciation rates, and risk-free rates.

4.2 Model calibration

I highlight differences in the capital-augmented production network by comparing results in (i) my disaggregated-capital model to two alternative models: (ii) a benchmark static model with disaggregated intermediate inputs but where capital is a separate primary factor in fixed supply, and (iii) a benchmark dynamic model where capital is an aggregate formed in the same proportions as the consumption good. I call model (ii) the static model and (iii) the aggregate-capital model. I calibrate models (ii) and (iii) to exactly match the same standard input-output data (but without matching disaggregated capital service flows). All three models can be represented by an appropriate choice of production and consumption coefficients in the same quantitative framework.

Calibration of the disaggregated-capital model. Section 3.1 discusses calibration of capital service coefficients and standard intermediate input and labor use coefficients in production, $\boldsymbol{\beta}$, and the related assumptions on asset depreciation and the risk-free rate $\boldsymbol{\delta}$, r^f. Besides these parameters, I compute final consumption shares $\boldsymbol{\alpha}$ analogously from final demand by sector in the augmented WIOD dataset (after stripping investment from final demand). Import shares $\boldsymbol{\pi}$ and labor income are directly observable in the data.

I use Caliendo and Parro (2014)'s estimates of sector-level trade elasticities $\boldsymbol{\theta}$. For a few, mostly non-traded, sectors that lack pre-existing estimates, I follow Costinot and Rodríguez-Clare (2014) and set $\theta_j = 5$. Lastly, given all the above parameters, I use the system of market-clearing equations behind Definition (1) to solve for the trade imbalances $\boldsymbol{D}$ that exactly rationalize the data in 1997 as a steady state of the global equilibrium. Table 5 and Appendix Table A.1 provide summary statistics at the country and sector levels respectively.

Calibration of the static model. For capital to be a primary factor, matching the standard input-output table requires treating investment expenditures as part of final demand. Consumption shares α_{nj} now differ and reflect relative expenditures over investment I as well as $C + G$. Proposition 1 changes accordingly. The goods market clearing condition simplifies to

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

where intermediate shares β^M_{njk} and aggregate capital intensities β^K_{nj} are unchanged. The unit price equation becomes

$$\hat{c}_{ij} = \hat{A}^{-1}_{ij} \hat{w}_i^{\beta^L_{ij}} \hat{r}_i^{\beta^K_{ij}} \prod_k \hat{P}_{ik}^{\beta^M_{ijk}},$$

where the change in the (aggregate) rental price, $\hat{r}$, is given by overall capital market clearing

$$\hat{r}_i \hat{K}_i r_i K_i = \sum_k \beta^K_{ik} X'_{ik}.$$

Calibration of the aggregate-capital model. Capital is a composite formed in the same proportions as the aggregate consumption good, C_n. Final consumption shares α_{nj} are the same as the static model, reflecting relative expenditures over investment I as well as $C + G$. Capital coefficients β^K_{njk} are now given by overall capital intensity β^K_{nj} apportioned over assets k in identical relative proportions in each sector j:

$$\beta^K_{njk} = \alpha_{nk} \beta^K_{nj}.$$

With this modification to capital coefficients, the goods market clearing condition and unit production cost equations are unchanged from Proposition 1, but depreciation rates are now specific to the composite capital, which I set at 0.13.

4.3 Propagation of shocks in general equilibrium

Figure 7 visualizes shock propagation under general equilibrium across (a) countries and (b) sectors. Panel (a) computes the impact on real income in country n from a 10 percent uniform productivity increase in all sectors in country i. Cells shaded blue indicate positive changes in real income, and cells shared in red indicate negative. An immediate takeaway is how populated the matrix is. Small and large countries alike transmit productivity shocks to the rest of the world,

even in instances where there is little direct trade. Direct import dependence is a weak correlate of a country's welfare elasticity to foreign productivity shocks. The R^2 between π_{ni} and the value of a cell in row i and column n is only 0.25.

In other words, indirect effects are strong in general equilibrium. Countries that supply very little into a given country can have outsized effects on welfare, and the outsized effects can be either positive or negative. Take, for example, a country like Hungary that imports very little from Slovakia ($\pi_{ni} = 0.004$) and Spain ($\pi_{ni} = 0.003$). A 10 percent productivity increase in Slovakia reduces welfare in Hungary by 0.5 percent but the same shock in Spain would raise welfare in Hungary by 0.08 percent.

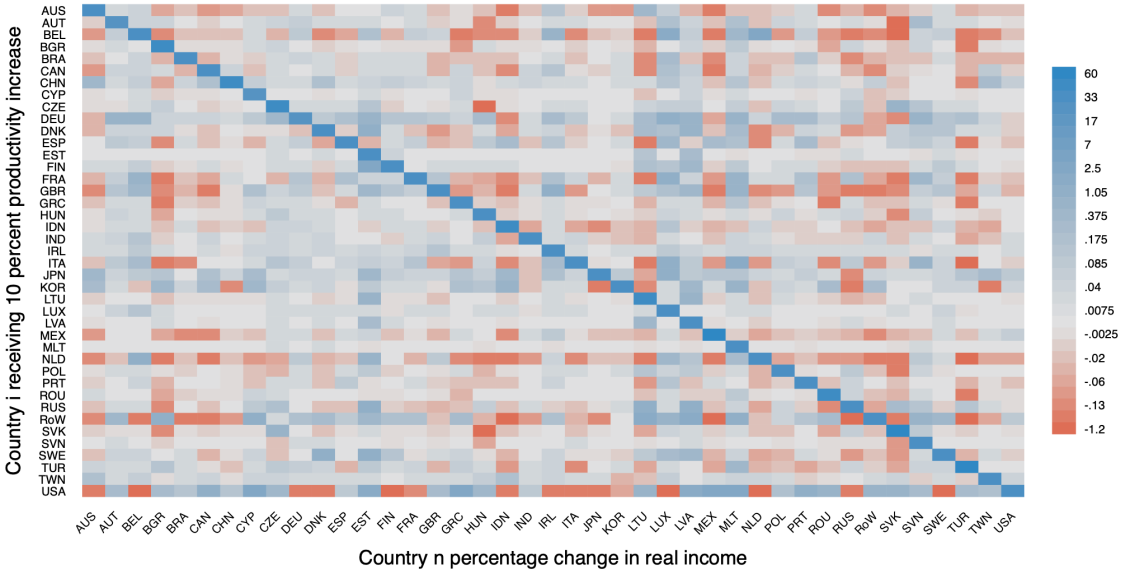
Through trade, increased productivity in one country can benefit or harm other countries' real incomes in two equally potent ways: (i) lower consumer and producer prices, and (ii) loss of terms of trade through competition. There are roughly the same share of countries with positive impacts as there are negative impacts. Countries' proximity to others in terms of their comparative advantage profile affect the relative strength of positive versus negative impacts. Interestingly, productivity increases in Japan cause welfare gains in 35 out of 40 other countries whereas a productivity increase in the Australia causes welfare to fall in 28 out of 40 other countries. At the same time, characteristics of the receiving country also determine whether it is more in competition with the rest of the world or more prone to benefit. Mexico and Indonesia are the biggest losers on average when productivity in other countries increase, whereas Malta and Luxemburg are among the biggest winners.

Appendix Figures C.1a and C.2a compare the cross-country elasticities against those under the two alternative calibrations. Absent the supply-use links from disaggregated capital, both positive and negative impacts are much less pronounced. I provide evidence in Section 4.5 that this occurs because trade-induced changes in comparative advantage are strongest when capital is disaggregated.

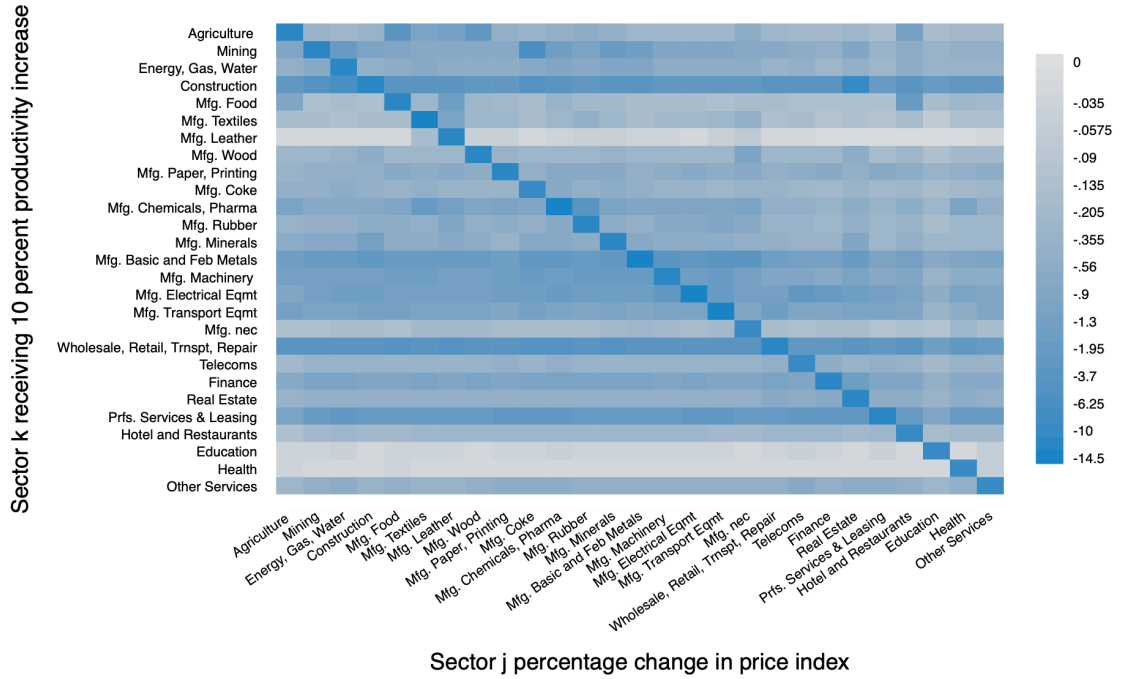
Panel (b) displays the impact on the average price index in sector j from a 10 percent uniform productivity shock in sector k in all countries. The figure reveals a dense web of strictly negative (beneficial) inter-sectoral cross-price-elasticities. Because the sector-specific shocks apply at once to all countries, terms of trade effects are negligible and all sectors stand to weakly benefit in response to a global sector-wide productivity increase. In most sectors, barring the most downstream ones like Leather, Education and Health, a positive shock in productivity lowers price indices in other sectors. Notably, capital-supplying sectors like construction, electrical equipment, transport equipment and professional services all transmit stronger price impacts to other sectors under the capital-augmented calibration. Appendix Figures C.1b and C.2b show that an equal productivity shock to these sectors generates much lower cross-sector transmission under the two alternative calibrations.

Figure 7: Propagation of Productivity Shocks across Countries and Sectors

(a) Impact of Productivity Shock in Country i on Real Income in Country n



(b) Impact of Productivity Shock in Sector k on the Price Index in Sector j



Notes: Panel (a) of this figure plots the impact of a 10 percent uniform productivity shock in each given country i on real income in country n. The change in real income is measured as the change in labor and net capital income divided by the change in the consumption price index. Panel (b) of this figure plots the impact of a 10 percent productivity shock in each given sector k on the average price index in sector j (averaged using country-consumption as weights).
Source: 1997 WIOD w/ socioeconomic accounts, select national accounts, and author's calculations.

4.4 Welfare gains from trade liberalization

I now consider the aggregate consequences. First, I use equation (12) to compute the gains from trade relative to autarky for each country. GFT_n measures the fraction of per-period consumption a representative household would be willing to give up to avoid moving from the current observed trade equilibrium and autarky, the preferred definition in Costinot and Rodríguez-Clare (2014). I convert this number into the gains from trade *relative to autarky*—defined as $\hat{C}_n = C_n/C_n^{\text{autarky}} = (1 - GFT_n)^{-1}$—which is easier to compare across models.

Table 5 columns (a) report values of C_n/C_n^{autarky} across the three model calibrations. Gains in the disaggregated-capital model are on average more than double the gains relative to autarky in the static model and 36 percent higher than the gains in the aggregate-capital dynamic model. There are a number of caveats with these calculations. First, the autarky counterfactual also removes trade imbalances, which conflates welfare results. Second, given the extreme shock of returning to autarky, calculations are sensitive to the Cobb-Douglas structure of preferences and production. For example, two countries, Luxembourg and Malta, have zero domestic production in certain sectors, causing estimates of the gains from trade to blow up.

I therefore simulate a smaller, uniform change in trade costs. I use Proposition 1 to derive outcomes in the counterfactual steady state when all bilateral cross-country trade costs fall by 10 percent in all sectors ($\hat{\tau}_{nij} = 0.9$), leaving imbalances unchanged and holding constant all other model primitives at 1997 values. Figure 8 charts each country's change in per-period welfare across the three model calibrations, also reproduced under columns (b) in Table 5. In the static model (in grey), the per-period gains from a 10 percent trade liberalization average 5.4 percent across countries. In dynamic model with aggregate-capital accumulation (in blue), the gains average 9.3 percent. In the disaggregated-capital calibration (in red), the gains average 10.1 percent, nearly double the gains in the static model and more than 8 percent higher than the gains in capital-aggregate model.

Comparison with static model calibration. Compared to the static model (ii), models (i) and (iii) relegate capital from a factor in fixed supply to a dynamic input that is used up in production and accumulated through trade and investment. The roughly doubling of the gains from trade is consistent with increased roundabout production. Investment goods from one sector provide capital services for downstream sectors. When trade lowers the prices of investment goods, it lowers costs of capital services in downstream sectors. These downstream sectors produce yet more inputs used as intermediates and capital, which lowers costs for yet more downstream sectors, *ad infinitum*. Models that treat investment as final-use and capital as a primary factor would miss these input-output loops. Because upstreamness increases weakly for every country-sector, gains from trade are naturally larger for every country in the sample, consistent with the amplification shown in Figure 6 under partial equilibrium.

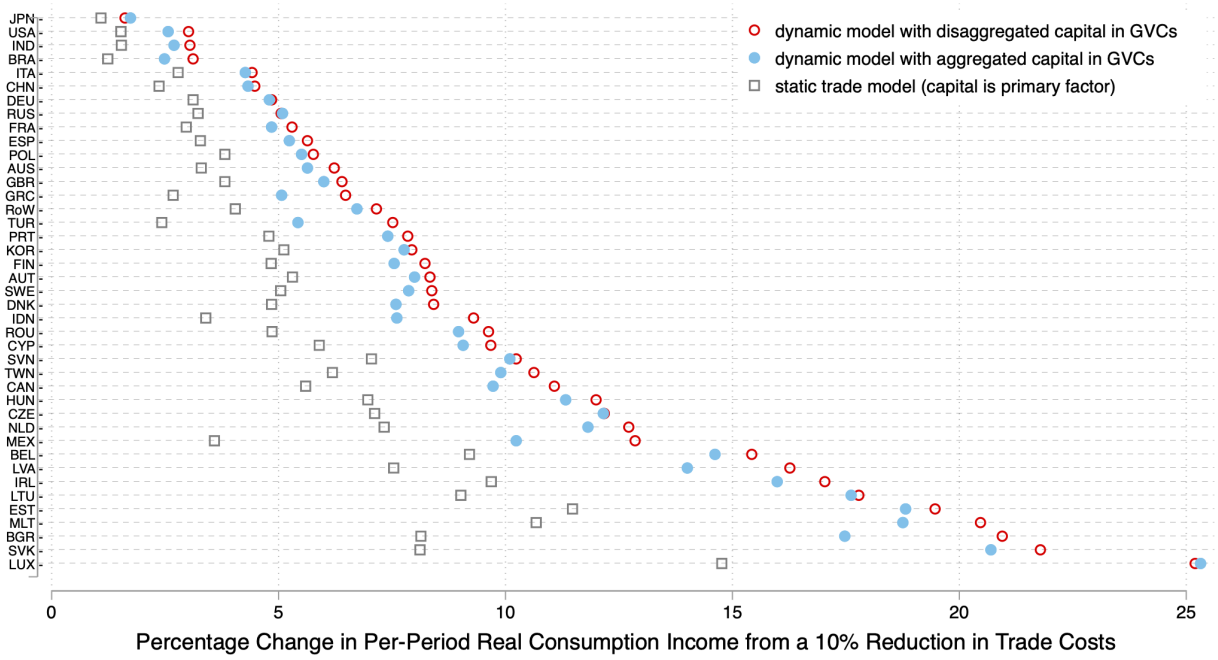
More interestingly, the additional gains from trade vary dramatically across countries. The red scatterplot in Figure 9 shows that a country's degree of additional welfare gains when moving

Table 5: Country-level economic characteristics in 1997 and model welfare gains from trade

		Value in 1997:			Percentage welfare gains, $100(\hat{C}_i - 1)$, by shock and model								
		β_i^K	β_i^M	π_i	(a) $\hat{\tau} = \infty$:			(b) $\hat{\tau} = 0.9$:			(c) $\hat{\tau}^{97\to07}$:		
					(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
AUS	Australia	0.18	0.52	0.06	28.0	14.9	25.3	6.2	3.3	5.6	4.2	3.0	4.8
AUT	Austria	0.18	0.45	0.13	109.2	57.8	97.0	8.3	5.3	8.0	21.7	12.9	20.1
BEL	Belgium	0.15	0.54	0.20	272.5	128.4	244.7	15.4	9.2	14.6	16.1	9.8	16.0
BGR	Bulgaria	0.22	0.58	0.18	229.8	42.0	107.9	20.9	8.1	17.5	97.5	19.3	44.8
BRA	Brazil	0.28	0.44	0.03	17.8	4.7	10.1	3.1	1.2	2.5	6.9	2.3	4.9
CAN	Canada	0.22	0.47	0.11	204.7	65.7	135.1	11.1	5.6	9.7	5.2	2.6	4.5
CHN	China	0.18	0.61	0.05	12.8	6.0	11.5	4.5	2.4	4.3	37.9	14.6	29.2
CYP	Cyprus	0.22	0.38	0.16	414.4	122.5	252.4	9.7	5.9	9.1	47.2	27.7	41.0
CZE	Czech Rep.	0.16	0.61	0.15	65.7	33.7	64.3	12.2	7.1	12.2	45.6	25.5	45.6
DEU	Germany	0.18	0.46	0.08	24.7	16.1	25.2	4.8	3.1	4.8	12.1	7.7	12.2
DNK	Denmark	0.18	0.46	0.11	92.7	50.6	86.1	8.4	4.8	7.6	12.8	6.9	11.3
ESP	Spain	0.17	0.50	0.08	39.5	21.2	34.7	5.6	3.3	5.2	12.7	7.2	11.7
EST	Estonia	0.17	0.58	0.21	275.9	107.4	229.7	19.5	11.5	18.8	148.7	72.5	132.5
FIN	Finland	0.16	0.52	0.11	46.3	22.8	36.5	8.2	4.8	7.5	18.3	9.2	14.8
FRA	France	0.20	0.47	0.07	29.6	14.9	24.9	5.3	3.0	4.8	8.4	4.8	7.9
GBR	UK	0.17	0.49	0.08	46.5	25.3	40.7	6.4	3.8	6.0	10.3	7.1	11.3
GRC	Greece	0.28	0.42	0.08	107.4	22.2	47.5	6.5	2.7	5.1	28.3	9.7	19.0
HUN	Hungary	0.17	0.56	0.18	91.0	40.0	74.4	12.0	7.0	11.3	84.6	37.6	72.0
IDN	Indonesia	0.25	0.50	0.08	49.4	17.4	38.0	9.3	3.4	7.6	9.1	4.1	8.5
IND	India	0.23	0.50	0.05	9.0	3.6	6.8	3.0	1.5	2.7	18.9	8.4	16.3
IRL	Ireland	0.19	0.55	0.21	245.6	96.1	188.2	17.0	9.7	16.0	19.5	11.6	19.1
ITA	Italy	0.16	0.50	0.07	22.4	13.4	20.8	4.4	2.8	4.3	8.7	5.5	8.6
JPN	Japan	0.22	0.47	0.03	3.5	2.5	4.3	1.6	1.1	1.7	2.6	1.5	2.7
KOR	Rep. of Korea	0.11	0.56	0.11	12.5	10.9	14.8	7.9	5.1	7.8	8.7	5.2	9.4
LTU	Lithuania	0.23	0.49	0.19	170.4	59.6	139.0	17.8	9.0	17.6	34.7	15.6	32.5
LUX	Luxembourg	0.19	0.55	0.33				25.2	14.8	25.3	140.2	44.4	83.8
LVA	Latvia	0.22	0.50	0.15	249.2	61.2	135.7	16.3	7.5	14.0	345.7	107.1	244.2
MEX	Mexico	0.37	0.43	0.11	178.5	21.2	75.5	12.8	3.6	10.2	32.1	6.6	19.8
MLT	Malta	0.22	0.49	0.25				20.5	10.7	18.8	158.4	59.1	115.3
NLD	Netherlands	0.16	0.51	0.17	141.3	76.9	134.7	12.7	7.3	11.8	9.4	5.3	8.4
POL	Poland	0.14	0.52	0.08	35.8	22.5	33.8	5.8	3.8	5.5	34.3	21.5	32.3
PRT	Portugal	0.16	0.52	0.11	79.9	41.5	70.4	7.8	4.8	7.4	22.4	12.5	19.7
ROU	Romania	0.21	0.56	0.11	47.0	17.3	35.2	9.6	4.8	9.0	52.8	18.8	37.7
RUS	Russia	0.21	0.48	0.04	31.0	14.8	26.6	5.1	3.2	5.1	7.5	4.3	7.5
RoW	Rest of World	0.21	0.48	0.11	71.7	32.3	59.4	7.1	4.0	6.7	48.6	23.8	41.9
SVK	Slovak Rep.	0.23	0.61	0.16	450.9	79.9	324.7	21.8	8.1	20.7	136.5	47.2	118.4
SVN	Slovenia	0.14	0.53	0.16	107.6	67.9	109.5	10.2	7.0	10.1	49.6	33.2	49.3
SWE	Sweden	0.17	0.51	0.12	40.5	23.3	37.7	8.4	5.0	7.9	10.0	5.6	9.2
TUR	Turkey	0.35	0.43	0.08	114.6	16.8	52.5	7.5	2.4	5.4	98.5	11.6	36.7
TWN	Taiwan	0.18	0.52	0.14	35.2	20.1	33.9	10.6	6.2	9.9	54.1	33.0	52.8
USA	United States	0.22	0.45	0.03	17.9	7.8	13.4	3.0	1.5	2.6	4.9	2.3	4.2
GDP-weighted average		0.21	0.48	0.07	38.9	16.8	30.7	4.9	2.7	4.5	15.2	7.3	12.9
Simple average		0.20	0.51	0.12	108.3	38.5	79.6	10.1	5.4	9.3	47.0	18.7	36.1

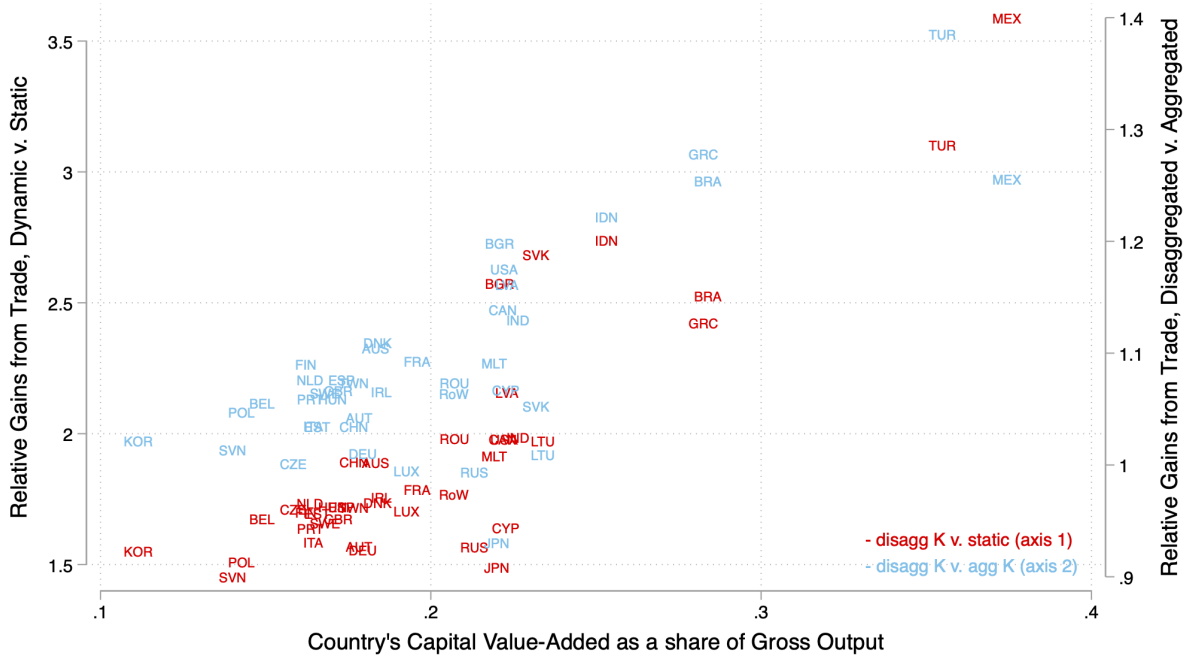
Note: This table summarizes characteristics and model-based counterfactual gains from trade by country. Capital intensity β_i^K denotes capital value-added as a share of gross output. Intermediate intensity β_i^M denotes intermediate expenditures as a share of gross output. Import intensity π_i denotes imports as a share of total expenditures. The change in welfare $100(\hat{C}_i - 1)$ is computed from equation (11) and Proposition 1 under three different shocks on trade costs: (a) autarky, where the $\hat{C}$ is the *inverse* of autarky welfare relative current welfare, (b) uniform 10 percent decline and (c) using Head-Reis revealed changes between 1997-2007. For each shock I compute gains under three model calibrations: (i) the baseline disaggregated-capital model, (ii) a static model with capital and labor as primary factors and investment as final use, and (iii) an alternative dynamic calibration with capital as an aggregate.

Figure 8: Welfare gains from uniform 10 percent reduction in global trade costs



Notes: This figure plots the change in per-period steady state real income for consumption ($100(\hat{C}_n - 1)$) by country from a 10 percent reduction in trade costs across all country pairs $n \neq i$ in all sectors, across three different model calibrations (shown in red, blue, and grey). Columns (b) in Table 5 display the underlying numbers.

Figure 9: Capital Intensity in Production Explains the Additional Gains from Trade



Notes: This figure plots the differences in the gains from trade across three model calibrations in Figure 8 on each country's capital intensity in production (measured as the ratio of capital income to gross output). The LHS y-axis and red scatter measures relative gains between models (i) and (ii), with and without capital accumulation. The RHS y-axis and blue scatter measures relative gains between models (i) and (iii), disaggregated and aggregated versions of modeling capital accumulation.

from static to dynamic calibrations is positively correlated with its capital intensity in production. Instead of treating each country's capital as a primary factor in fixed supply, in a dynamic setting capital-intensive producers have their marginal costs disproportionately lowered by trade liberalization, and, given that most of production is sold at home, ends up benefiting domestic sectors and consumers downstream. To the extent output is sold abroad, either in the capital-supplying sector or in domestic downstream sectors, lower production costs also generate terms-of-trade effects that increase labor and capital incomes. Welfare gains in capital-intensive, intermediate-light countries like Mexico ($\beta_n^K = 0.37, \beta_n^M = 0.43$) are 3.6 times higher, whereas relative welfare gains in intermediates-intensive, capital-light countries like Korea ($\beta_n^K = 0.11, \beta_n^M = 0.56$) are only 1.6 times higher. If any part of these differences in capital-versus-intermediate intensity are due to accounting rather than technological differences, standard calculations of the gains from trade would be understated for Mexico and overstated for Korea *even if* one were interested in purely short-run, static-model changes.

Comparison across dynamic model calibrations. The blue scatterplot in Figure 9 shows that the difference in welfare gains between model (i) and (iii) is still increasing with a country's capital intensity in production. Both models feature the same capital intensity β_{nj}^K in each country-sector

n, j; both models allow capital to be accumulated and traded; both models exactly match the same data in conventional input-output tables. The only difference is in the relative *composition* of capital assets k used in each sector j. The disaggregated-capital calibration allows sectors to use capital assets k with different relative intensities, whereas the aggregate-capital calibration assumes (relying on just the conventional input-output tables) that each sector j uses capital assets k with the same relative intensities α_{nk} as in final consumption. This difference alone causes gains to be on average 8 percent higher (or 9 percent higher when GDP-weighted) in the disaggregated model calibration. Gains are higher in all but three countries: Japan, Russia, and Luxembourg.

The key mechanism responsible for this difference is that heterogeneous capital-use coefficients induce larger changes in comparative advantage. Under the aggregate-capital calibration, Mexico would experience lower user costs of capital proportionally for *all* its sectors. Under the disaggregated-capital calibration, Mexico could experience extreme reductions in user costs of capital for a few sectors that use traded-capital assets, and mild reductions in other sectors. In a world with trade, a country benefits more from the latter case as terms-of-trade effects work more to its advantage when it can specialize.

4.5 Production reallocation and shifting comparative advantage

I evaluate the disaggregated-capital model's key mechanism—trade-induced comparative advantage—and quantify and test its economic significance in the data. I apply the Head and Ries (2001) methodology to estimate more realistic changes in bilateral country by sector trade costs between 1997 and 2007:

$$\left(\hat{\tau}_{nij}^{97\to07}\hat{\tau}_{inj}^{97\to07}\right)^{-\theta_j} = \left(\frac{\hat{\pi}_{nij}\hat{\pi}_{inj}}{\hat{\pi}_{nnj}\hat{\pi}_{iij}}\right)^{97\to07}, \tag{13}$$

assuming that domestic trade costs remain unchanged in each country ($\hat{\tau}_{nnj}^{97\to07} = 1$).[15] In addition, I assume that changes in bilateral frictions are symmetric, so $\hat{\tau}_{nij}^{97\to07} = \hat{\tau}_{inj}^{97\to07}$, and I winsorize at the 2.5 and 97.5 percentiles of the distribution of $\hat{\tau}_{nij}^{97\to07}$. On average, revealed trade costs fell 12 percent during this period. I use this estimate of $\hat{\tau}_{nij}^{97\to07}$ as shocks to the model's initial equilibrium calibrated to 1997. I hold all other model primitives constant at their 1997 values to isolate the impact of trade liberalization on the global production network.

Table 5 columns (c) display country-specific estimates of welfare gains from $\hat{\tau}_{nij}^{97\to07}$. Table 6 panel (a) aggregates these welfare gains across countries using their 1997 GDP as weights. First, row (v) indicates that welfare gains in the disaggregated-capital model are 20 percent higher than the aggregate-capital case. This is a higher premium than the 8 percent found in the uniform-trade liberalization scenario, suggesting that the revealed changes in trade costs were biased in favor of capital suppliers and users in the network.

[15] This assumption benchmarks changes in international trade frictions *above and beyond* any changes in domestic trade frictions. The imputed $\hat{\boldsymbol{\tau}}$ shocks likely under-represent the true effects of globalization. For example, if transportation costs fell proportionally for both domestic ($i = n$) and international ($i \neq n$) routes, the implied $\hat{\tau}_{ni}$ would equal 1. Indeed, imputed trade costs *rose* (i.e. $\{\hat{\tau}_{nij}\}_{n\neq i,j} > 1$) for 31 percent of the sample, likely containing instances where domestic frictions fell faster than international frictions.

Table 6: Welfare Gains from Observed Globalization, 1997-2007

	Model Calibration:					
	Disaggregated K		Aggregate K		Static	
Panel (a): Decomposing Welfare						
$100(\hat{C}-1)$ evaluated at:	old w	new w'	old w	new w'	old w	new w'
Cumulative impacts of:						
(i) direct effect of $\hat{\tau}^{97\to07}$	3.1		4.0		4.0	
+ (ii) intermediate input costs	6.4	1.1	7.9	3.3	7.9	5.0
+ (iii) capital service costs	17.6	5.0	14.4	5.5	7.5	3.3
+ (iv) capital incomes	20.3	7.5	14.9	6.4	7.5	4.9
+ (v) labor incomes (= total):		15.2		12.9		7.3
Panel (b): Incomes						
Change in						
Global labor income (%)	9.19		6.88		3.84	
Global capital income (%)	11.37		7.53		3.82	
Global labor share	-0.47		-0.14		0.01	
Panel (c): Model validation						
Regression of $\hat{X}_{nj}^{\text{data, 97-07}}$ on:						
$\hat{X}_{nj}^{\text{model}}$	0.201***	0.338***	0.178***	0.293***	0.084	0.021
	(0.056)	(0.095)	(0.057)	(0.102)	(0.050)	(0.047)
Sector fixed effects	N	Y	N	Y	N	Y
R^2 (within)	0.032	0.063	0.022	0.038	0.005	0.001

Note: This table presents quantitative results from three different calibrations that match the same conventional world input-output table data in 1997: the disaggregated-capital model uses capital-augmented input-output coefficients and solves for counterfactuals using the exact equations in Proposition 1; the aggregate-capital model retains the same capital intensities β_{nj}^{K} and investment shares as in the conventional WIOD but assumes that each sector uses underlying capital assets in the same relative intensities; the static model assumes capital is a primary factor in fixed supply while investment purchases are part of final demand. Panel (a) decomposes the percentage change in real consumption income (welfare $100(\hat{C}-1)$ in equation 11) into a sequence of cumulative impacts from row (i) to row (v). Each row can be evaluated at old wages w in the initial equilibrium or final wages w' in the new equilibrium. Panel (b) presents results on the percentage point change in the global labor share, and constituent percentage changes in labor and capital (nominal) incomes. Panel (c) regresses changes in country-sector output in the data on that in the model across $N = 1105$ country-sector observations and using output in 1997 as weights. Robust standard errors are shown in parentheses. *** p<.01, ** p<.05, * p<.1

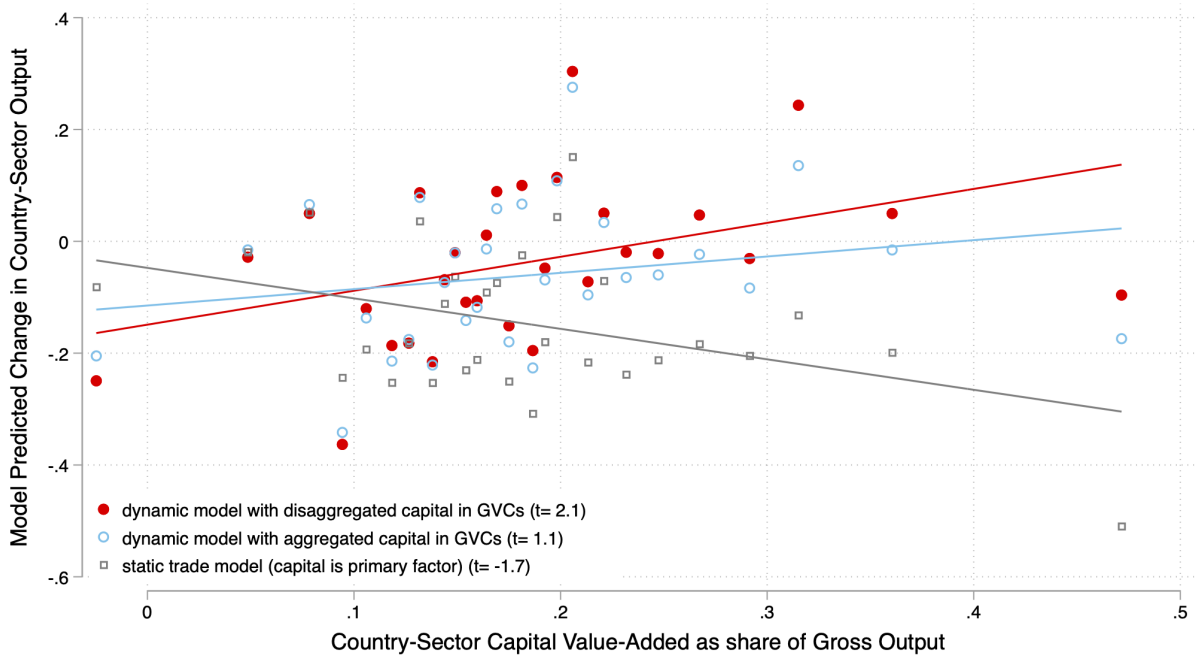
Rows (i)-(v) in Table 6 decompose the total welfare change into a sequence of cumulative impacts. Row (i) shows the direct effect of the change in trade costs on the consumption price index, holding all other variables (e.g., wages, incomes, intermediate input and capital rental prices) unchanged.[16] Row (ii) incorporates adjustment in intermediate inputs under roundabout production. Row (iii) additionally allows capital service costs to adjust, and row (iv) additionally allows capital incomes (part of which are used for consumption) to adjust. Finally, row (v) displays the cumulative change in welfare after labor incomes adjust. At each of these intermediary rows (ii) to (iv), I compute the change in welfare using both wages w in the old equilibrium and w' in the new equilibrium. Given that labor is a fixed factor, wages rise in general equilibrium to offset excess labor demand. This has a counter-veiling effect, raising prices of both intermediate inputs, investment goods, final goods, and also affecting capital incomes.

Several results are noteworthy. Moving from row (i) to row (ii), the gains from trade roughly double from adding roundabout production in intermediate inputs. This effect is consistent across all three model calibrations since they all contain the same intermediate input coefficients. The direct effect of trade cost reductions on consumer prices are dwarfed by the indirect effects on input prices (both intermediates and capital) through the global production network. In the aggregate-capital model, total welfare change by row (v) is 3.2 times the direct effect in row(i), whereas in the disaggregated-capital model, total welfare change is nearly 5 times the direct effect. A substantial part of the increase comes from the added effect of endogenous capital service costs, which lowers production costs everywhere. In contrast, in the static model the capital factor is fixed in supply, so the cost of capital services changes purely to offset increased demand, in the same way as labor. The amplification effect of capital on welfare gains is consistent with Figure 6, where elasticities of production costs to foreign shocks are nearly three times higher moving from the intermediates-only calibration to both capital and intermediates.

When capital is disaggregated, equilibrium changes in capital service costs contribute much more to welfare gains. The contribution of capital incomes to welfare is also much larger—2.5 percentage points at new wages compared to 0.9 percentage points in the capital-aggregate model. This difference comes primarily from increased production reallocation in the disaggregated-capital model, where trade liberalization causes comparative advantage to shift in favor of capital-intensive producers in each sector. Aggregating capital mutes this reallocation. When capital is aggregated, all sectors use capital with the same relative intensities and experience similar relative declines in producer cost. Reallocations in market share are less likely to occur because any broad-based cost-advantages are nullified by the change in the country's wage in general equilibrium. In comparison, when capital is disaggregated, some sectors gain more at the expense of others, so that even after general equilibrium changes in wages, the market share advantage in the leading sector remains.

[16]The direct effect is slightly different between the disaggregated-capital and the aggregated-capital frameworks because the calibration of α_{nj} in the disaggregated-K model is based on relative C+G expenditures, whereas the calibration of α_{nj} in the aggregate-K model is based on relative C+I+G expenditures. This latter choice is consistent with existing capital-aggregate models and in this way both models can be calibrated to match the same conventional I/O table.

Figure 10: Model Mechanism: Capital-intensive Producers gain market share



Notes: This figure plots binscatter regressions of the model's predicted change in output, log $\hat{X}_{ij}$, against the country-sector's capital intensity in production, β_{ij}^K, absorbing sector fixed effects, for each of the three model calibrations.

Figure 10 visualizes the trade-induced gains in market share for capital-intensive producers. I regress each country-sector's model-predicted log change in output (log $\hat{X}_{ij}$) against its 1997 capital intensity (β_{ij}^K), controlling for sector fixed effects so as to measure changes in market *shares* (output relative to other producers in the same sector). The red line shows a statistically positive and significant regression fit ($t = 2.1$) in the disaggregated-capital calibration. In contrast, the blue and grey lines show an insignificant regression fit ($t = 1.1$ and $t = -1.7$) from predictions in the capital-aggregate and static calibrations.[17]

One corollary of the trade-induced reallocation towards capital-intensive producers is that the global labor share falls. Different from arguments invoking labor-capital substitutability (Karabarbounis and Neiman, 2013), in my model this occurs even as production functions are everywhere Cobb-Douglas. Trade generates a form of substitutability across countries as capital reallocates to the most cost-effective country in each sector. Within each country, this reallocation tends to shift output towards the country's respective set of capital-intensive sectors.[18] Again, unique to the fully-disaggregated capital calibration, 30 out of 41 countries experience a decline in their labor

[17] I choose overall capital intensity in production as a fair common regressor across the three models. A more accurate predictor is *imported* capital intensity, which induces an even stronger relationship with reallocation in the disaggregated-capital calibration ($t = 4.4$) but given its specificity to the disaggregated-capital model I refrain from using it to compare across models.

[18] Technically, this effect can be offset if intermediate inputs are tradable and industries intensive in intermediate input use happen to be also intensive in labor. This correlation, however, is not present in the data.

share. Table 6 panel (b) reports that the (weighted) global labor share falls by 0.47 percentage points, and the unweighted average decline is 1.54 percentage points.

Finally, I put model's predictions for trade-induced reallocation to the test. One advantage of using *revealed* changes in trade costs is that model predictions can be compared to actual changes in the data. Ten years in the data is long enough for producers to either build up new capital or run down capital stocks, consistent with the model's focus on the steady state. The last rows of Table 6 display results from regressing observed changes in $\hat{X}_{ij}$ between 2007 and 1997 against model-predicted changes in $\hat{X}_{ij}$ from the globalization shock alone. By incorporating the capital-augmented input-output network, the globalization shock explains more than six percent of the changes in countries' global market shares in each sector. In comparison the aggregate-capital calibration explains three percent, and the static calibration less than one percent.

Conclusion

Capitalization in the national accounts obfuscates measurement and calibration of sectoral linkages. This paper overcomes the measurement challenge. I offer a unified treatment of capital and intermediates in a fully disaggregated dynamic general equilibrium model of global production. I assemble data on bilateral gross fixed capital formation for 40 countries and leverage the equilibrium conditions in the model to construct the first global input-output matrix of capital service coefficients. I use these capital coefficients to augment standard input-output matrixes, revealing a dense, heterogeneous network of inter-sectoral, inter-country supplier-buyer relationships across capital producers and intermediate producers. As a proof of concept, I deploy the capital-augmented model to revisit standard questions of shock propagation and the gains from trade liberalization. In doing so I bridge two existing literatures: models of production networks that embrace sectoral heterogeneity but ignore capital, and models with dynamic capital accumulation but without sectoral disaggregation. I find that both dynamics and disaggregation increase the welfare impact of trade and productivity shocks.

This paper opens numerous avenues for further research. The methodology for developing capital input-output tables is general and can be applied to an even wider set of countries and data from contemporaneous years. More progress can be made by linking this dataset with data on international capital flows (Florez-Orrego et al., 2023) and cross-border multinational activity, especially the transfer and trade of intellectual property (McGrattan and Prescott, 2010; Keller and Yeaple, 2013; Arkolakis et al., 2018). The capital input-output coefficients can be used to revisit measures of the upstream and downstream effects of trade shocks (especially the China shock, as in Acemoglu et al., 2016, given China's upstreamness-adjustment), determinants of spatial agglomeration (Ellison et al., 2010) and international correlations over the business cycle (Huo et al., 2023). Finally, it would be fruitful to extend the simple model environment to incorporate transition dynamics (following Caliendo et al., 2019; Kleinman et al., 2023) or endogenous trade imbalances (Dix-Carneiro et al., 2023).

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ONLINE APPENDIX

A Data

Section A.1 describes data that constitute the "standard input-output table" used in the paper. Section A.2 describes the algorithm used to construct the global investment matrix. Section A.3 describes how I use the global investment matrix to compute the matrix of capital service flows and capital coefficients.

A.1 World Input-Output Database

These data come from the 2013 release of the World Input Output Database (WIOD) constructed by Timmer et al. (2015), covering the years 1995-2011. I aggregate the native industry classification in the WIOD to a 27-sector 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 sector, industry, and commodity nomenclature in country-specific national accounts. The WIOD comprises data from 41 economic regions: 40 countries plus a rest-of-the-world aggregate. I use these native definitions throughout my analysis. Table 5 and Table A.1 provide the full list of countries and sectors along with key summary statistics. The WIOD has been described and used in prior quantitative work surveyed in Costinot and Rodríguez-Clare (2014) and Antràs and Chor (2022).

The native tables in the WIOD report for each using sector-country only total value-added instead of value-added broken out by labor and capital. I use the complementary socio-economic accounts data in the WIOD, which contain separate estimates of labor compensation by sector in each country. I define the labor share per sector in each country as total labor compensation as a share of total value added, and capital shares of value-added as 1 minus the labor share. I winsorize extreme values of the the labor share of value-added so all labor shares fall within 0.01 and 0.99. This winsorization affects 3 percent of country-industry observations in the dataset, mostly observations where labor compensation is higher than total value-added.

Finally, I make a few adjustments to the WIOD to make it consistent with the model. I drop the following '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.

A.2 Constructing the Global Bilateral Investment Network

As part of the standard input-output tables, the WIOD contains data on new investment $(P_{nik}I_{nik})_{\text{WIOD}}$, or gross fixed capital formation (GFCF), by supplying sector $k \in \mathcal{K}$ and supplying and consuming countries, n, i.

The algorithm I develop apportions this expenditure value $(P_{nik}I_{nik})_{\text{WIOD}}$ across the remaining dimension—using sectors $j \in \mathcal{K}$. First, since supplying-level detail i is computed by apportioning national investment by supplying sector $(P_{nk}I_{nk})_{\text{WIOD}}$ using import shares, I start with $(P_{nk}I_{nk})_{\text{WIOD}}$ in this algorithm and save the apportioning by supplying country using π_{nik} for the last step.

I start with data on $(P_{nk}I_{nk})_{\text{WIOD}}$ and compute bilateral investment flows $P_{n,k}I_{n,jk}$ as:

$$P_{n,k}I_{n,jk} = \omega_{n,jk}\,(P_{n,k}I_{n,k})_{\text{WIOD}} \qquad \forall j \in \mathcal{K},$$

where apportioning shares $\omega_{n,jk}$ satisfy $\sum_j \omega_{n,jk} = 1\ \forall n, k$. Then, assuming import proportionality (consistent with existing practice in the WIOT to apportion intermediate input use or final use into supplying

Table A.1: List of sectors and their associated statistics and parameters in 1997

				share of output supplied as:		share of expenditures on:	
Sector:	δ_k	θ_k	π_k	investment	final demand	capital $\left(\vec{\beta}^K_{\cdot j}\right)$	labor $\left(\vec{\beta}^L_{\cdot j}\right)$
Agriculture	0.02	8.11	0.08	0.02	0.37	0.20	0.38
Mining	0.04	15.72	0.26	0.06	0.03	0.34	0.26
Energy, Gas, Water	0.02	5.00	0.01	0.01	0.34	0.37	0.16
Construction	0.03	5.00	0.00	0.82	0.01	0.09	0.33
Mfg. Food	0.16	2.55	0.11	0.00	0.64	0.14	0.14
Mfg. Textiles	0.16	5.56	0.32	0.01	0.50	0.11	0.23
Mfg. Leather	0.16	5.56	0.37	0.00	0.58	0.09	0.20
Mfg. Wood	0.16	10.83	0.15	0.06	0.07	0.11	0.23
Mfg. Paper, Printing	0.16	9.07	0.13	0.03	0.18	0.14	0.24
Mfg. Coke	0.16	51.08	0.16	0.00	0.30	0.21	0.06
Mfg. Chemicals, Pharma	0.16	4.75	0.29	0.01	0.23	0.18	0.15
Mfg. Rubber	0.16	1.66	0.18	0.02	0.13	0.13	0.22
Mfg. Minerals	0.16	2.76	0.12	0.01	0.09	0.17	0.23
Mfg. Basic and Feb Metals	0.09	7.99	0.19	0.07	0.04	0.12	0.21
Mfg. Machinery	0.13	1.52	0.33	0.44	0.12	0.11	0.25
Mfg. Electrical Eqmt	0.17	10.60	0.40	0.29	0.13	0.12	0.21
Mfg. Transport Eqmt	0.11	0.37	0.32	0.26	0.28	0.09	0.18
Mfg. nec	0.13	5.00	0.26	0.18	0.46	0.10	0.27
Wholesale, Retail, Trnspt, Repair	0.10	5.00	0.07	0.06	0.42	0.21	0.40
Telecoms	0.02	5.00	0.03	0.01	0.35	0.32	0.31
Finance	0.16	5.00	0.04	0.00	0.36	0.28	0.32
Real Estate	0.03	5.00	0.00	0.03	0.70	0.72	0.06
Professional Services and Leasing	0.33	5.00	0.06	0.09	0.12	0.20	0.42
Hotel and Restaurants	0.16	5.00	0.02	0.00	0.74	0.14	0.35
Education	0.16	5.00	0.01	0.00	0.94	0.07	0.70
Health	0.16	5.00	0.00	0.00	0.95	0.13	0.49
Other Services	0.16	5.00	0.01	0.01	0.83	0.14	0.50

Notes: This table summarizes parameters and characteristics of the 27 sectors $j, k \in \mathcal{K}$ in this paper. Sectors are a slight aggregation of the WIOD nomenclature to be concordable with country-specific GFCF data. Depreciation rates δ_k are taken from the BEA and from Corrado et al. (2009). Trade elasticities θ_k are taken from Caliendo and Parro (2014). Remaining data come directly from the WIOD, and data shown are weighted averages over all 41 countries in the WIOD (see Table 5). Trade shares π_k are computed as the share of output that is traded. The last four columns provide (i) the share of output consumed by type of use: investment and final demand (with intermediate inputs making up the remainder—omitted as shares sum to 1), and (ii) the production expenditures on capital and labor as a share of sector gross output (with intermediate inputs making up the remainder).
Source: WIOD, OECD, country-specific national accounts, and existing literature.

countries), I multiply by π_{nik} to compute the value of gross fixed capital formation in full bilateral supplying country-sector (i,k) to using country-sector (n,j) detail:

$$P_{ni,k}I_{ni,jk} = \pi_{nik}\omega_{n,jk}\left(P_{nk}I_{nk}\right)_{\text{WIOD}}.$$

The key apportioning shares $\omega_{n,jk}$ are constructed differently depending on what (and whether) additional data sources are available for each country. For each country I set apportioning shares to match as much bilateral country-specific data as is available, before resorting to the model and additional assumptions to fill remaining gaps. I describe below the method I use for different sets of countries in sequence of data availability. Notationally, I use large parentheses around the value of investment $\left(P_{nk}I_{njk}\right)_{\text{source}}$ to denote observable data on investment from a particular external source and distinguish it from the model-predicted value (without parentheses).

USA. For the USA, I use the BEA's capital flow tables in 1997 (see Meade et al., 2003 for more details). These data show the amount of bilateral flows of new investment, $\left(P_{n,k}I_{n,jk}\right)_{USA}$, conducted by each of 123 producing industries on each of 180 different types of capital assets in that year. I aggregate this data into the 27-sector classification $\mathcal{K}$. I compute $\omega_{USA,jk}$ as

$$\omega_{USA,jk} \equiv \frac{\left(P_{n,k}I_{n,jk}\right)_{USA}}{\sum_j \left(P_{n,k}I_{n,jk}\right)_{USA}},$$

for all sectors k in the BEA where total investment is positive. Note that due to differences in construction, the BEA capital flow tables do not necessarily agree with the WIOD in terms of total investment even at the unilateral supplying-sector k level. Two edge cases can arise: (i) the BEA reports a total investment of 0 in a given sector k while the WIOD reports positive investment, and (ii) the BEA reports positive while the WIOD reports zero. To be consistent with remaining entries in the WIOD (intermediate input use, gross output, expenditures, etc) I rely on the WIOD as the "ground truth" and use the BEA data only for apportioning purposes. For sectors k that fall under case (i), when BEA information is not usable, I construct alternative apportioning shares as the theory-predicted steady-state share of investments in asset k made by sector j if all sectors used capital services in the same relative proportions:

$$\omega_{USA,jk} \equiv \frac{\beta^K_{USA,j}X_{USA,j}}{\sum_j \beta^K_{USA,j}X_{USA,j}}.$$

Note that this is the assumption that "aggregate-capital" model-calibration implicitly applies to all sectors k. Sectors k that fall under case (ii), when the WIOD reports zero investment, pose no problem. Regardless of the value of ω taken from the BEA, they will simply be multiplied into zero total investment in the WIOD.

Once construction of $\omega_{USA,jk}$ is complete, I apply the step in Section A.3 to compute US production coefficients on capital services, $\beta^K_{USA,jk}$.

Mexico. Mexico's National Institute of Statistics and Geography (NISG) provides analogous data on gross-fixed capital formation (value of new investment) by origin and destination industry (at three-digit NAICS, beginning 2003). I aggregate this data into the 27-sector classification $\mathcal{K}$. But since Mexico provides this data only from 2003 onwards, I "back-cast" sectoral flows in any year t to 1997 (base-year) levels by

dividing through sector j's growth rate between 1997 and t:

$$P_{MEX,k,1997}I_{MEX,jk,1997} = \left(P_{nk,t}I_{njk,t}\right)_{MEX} \frac{X_{MEX,j,1997}}{X_{MEX,j,t}}.$$

The implicit assumption behind this back-casting is that given the Cobb-Douglas production structure, rental payments are a constant fraction of gross output, and in steady state, the value of investment is a constant fraction of rental payments (holding constant the risk-free and depreciation rates). Note that under Cobb-Douglas, any changes over time in the relative prices of different types of investment goods $P_{k,t}$ and $P_{k,t'}$ has no impact on the relative *value* of investment, $P_{k,t}I_{jk,t}$ versus $P_{k,t'}I_{jk,t'}$. In practice I use data from each of three years $t = 2003, 2004, 2005$ to construct an average measure of $\left(P_{nk,1997}I_{njk,1997}\right)_{MEX}$.

After obtaining estimates of $P_{MEX,k,1997}I_{MEX,jk,1997}$, I apply the same steps as for the USA to compute $\omega_{MEX,jk}$. Just like for the USA, an edge case (i) can occur where the NISG data source reports a total investment of 0 for asset k, whereas the WIOD reports positive investment in that sector. For these sectors k I construct alternative apportioning shares as the theory-predicted steady-state share of investments in asset k made by sector j if each sector in Mexico used capital services in the same relative proportions as the US:[19]

$$\omega_{MEX,jk} \equiv \frac{\frac{\beta^K_{USA,jk}}{\sum_k \beta^K_{USA,jk}} \beta^K_{MEX,j} X_{MEX,j}}{\sum_{j'} \frac{\beta^K_{USA,j'k}}{\sum_k \beta^K_{USA,j'k}} \beta^K_{MEX,j'} X_{MEX,j'}}.$$

Notice that the construction of ω in the edge case above still respects the fact that sectors j can be more capital intensive overall in Mexico compared to the US. US production coefficients are only used in a relative sense (intensity of services from capital k *relative* to other types of capital services k'). Just like for the USA, edge case (ii) where the WIOD reports zero investment is trivial as there is zero investment to apportion.

Once construction of $\omega_{MEX,jk}$ is complete, I apply the step in Section A.3 to compute Mexican production coefficients on capital services, $\beta^K_{MEX,jk}$.

Select OECD Countries. For a large number of remaining countries I use similar bilateral investment data from country-specific national accounts that are already collected by the OECD. The OECD provides one classification system (transaction codes) for supplying sectors and another classification system (activity codes) for using sectors. But this data is reported in varying tiers of aggregation across countries, including sometimes as implicit residuals that correspond to groupings of (omitted) transaction and activity codes within a given tier.

Instead of aggregating this data to the same (aggregated) tier for each country, I use as much country-specific detail as possible. For each country, for each side of the input-output relationship (supplying and using), I create two concordances: (i) a `m:1` concordance that aggregates the native transaction codes to a superset of supplying industries $s \in \mathcal{S}$, where $\mathcal{S}$ is chosen as the least amount of aggregation needed to have (ii) a `m:1` concordance mapping each final sector code $k \in \mathcal{K}$ to map to at most one $s \in \mathcal{S}$. I make an analogous two concordances for the using side: (i) a `m:1` concordance that aggregates the native activity codes to a superset of industries $l \in \mathcal{L}$, where $\mathcal{L}$ is chosen as the least amount of aggregation needed to have

[19] The relationship between $r_{MEX,k}K_{MEX,jk}$ (proxied by $\frac{\beta^K_{USA,jk}}{\sum_k \beta^K_{USA,jk}} \beta^K_{MEX,j} X_{MEX,j}$) and $P_{MEX,k}I_{MEX,jk}$ of course requires an adjustment by a factor of $\frac{\delta_k}{\delta_k + r^f}$ but since ω are shares within each supplying sector k, the adjustment factor $\frac{\delta_k}{\delta_k + r^f}$ is present in both the numerator and denominator and cancels out.

(ii) a m:1 concordance mapping each final sector code $j \in \mathcal{K}$ to map to at most one $l \in \mathcal{L}$. In other words, $\mathcal{L}$ is weakly more aggregated than both the native transaction codes and $\mathcal{K}$, and $\mathcal{S}$ is weakly more aggregated than both the native activity codes and $\mathcal{K}$. $\mathcal{L}$ and $\mathcal{S}$ vary for each country due to differences in the level of aggregation provided. The typical country has eight different types of assets in $\mathcal{S}$ and 15 different using industries in $\mathcal{L}$.

Given this $\mathcal{L}_n \times \mathcal{S}_n$ bilateral investment matrix for each country n, I first compute $l \times s$-level apportioning shares: the share of total investment $P_s I_s$ in asset s made by sectors l:

$$(\omega_{nls})_{OECD} \equiv \frac{(P_{ns} I_{nls})_{OECD}}{\sum_l (P_{ns} I_{nls})_{OECD}}.$$

Since l and s are more aggregated sector classifications compared to j and k, the apportioning shares above $(\omega_{nls})_{OECD}$ offer only partial discipline on the final apportioning shares ω_{njk}.

I compute final apportioning shares ω_{njk} in a way such that the share of investments in assets k within class $k \in s$ made by industries j within cluster $j \in l$ always match the above $(\omega_{n,ls})_{OECD}$. In other words, the apportioning shares must satisfy

$$\frac{\sum_{j \in l} \sum_{k \in s} \omega_{njk} (P_{n,k} I_{n,k})_{\text{WIOD}}}{\sum_{k \in s} (P_{n,k} I_{n,k})_{\text{WIOD}}} = (\omega_{nls})_{OECD} = \frac{(P_{ns} I_{nls})_{OECD}}{\sum_l (P_{ns} I_{nls})_{OECD}}. \tag{14}$$

It remains to find ω_{njk} such that the above is satisfied. Absent this additional l, s-level of data, one way to construct apportioning shares would have been to assume, just as with Mexico edge case (i), that sector j in country n uses capital services in the same relative proportions as sector j in the U.S., and therefore construct theory-predicted investment levels in steady state as

$$\widetilde{P_{n,k} I_{n,jk}}^{ss} = \frac{\beta^K_{USA,jk}}{\sum_k \beta^K_{USA,jk}} \beta^K_{n,j} X_{n,j} \frac{\delta_k}{\delta_k + r^f}.$$

In the absence of any country bilateral-level investment data, these values of $\widetilde{P_{n,k} I_{n,jk}}^{ss}$ can be used to construct apportioning shares $\omega_{n,jk}$ (as was the case with Mexico case (i)). However, to satisfy the constraint imposed by *observed* shares of investment at a more aggregated level in equation (14), I adjust $\widetilde{P_{n,k} I_{n,jk}}^{ss}$ by scaling factors $\chi_{n,ls}$ and solve for the $\mathcal{L}_n \times \mathcal{S}_n$ scaling factors χ_{ls} that exactly satisfy the constraint in equation (14):

$$\begin{aligned} \chi_{n,ls} &= \underset{\{\chi_{nls}\}_l}{\arg\min} \left\| \frac{\sum_{j \in l} \sum_{k \in s} \omega_{njk} (P_{n,k} I_{n,k})_{\text{WIOD}}}{\sum_{k \in s} (P_{n,k} I_{n,k})_{\text{WIOD}}} - (\omega_{nls})_{OECD} \right\| \qquad \forall s, n, \\ \omega_{njk} &\equiv \frac{\widetilde{P_{n,k} I_{n,jk}}^{ss} \chi_{n,l(j)s(k)}}{\sum_{j'} \widetilde{P_{n,k} I_{n,j'k}}^{ss} \chi_{n,l(j')s(k)}}. \end{aligned} \tag{15}$$

where recall that $l(j)$ is the unique sector l that using sector j maps into, and $s(k)$ is the unique sector s that supplying sector k maps into. Scaling factors χ_{nls} essentially adjust upwards and downwards the model-predicted use of assets $k \in s$ by sectors $j \in l$ compared to other sectors $j' \in l'$, such that the share of s used by l versus l' after apportioning in the WIOD data exactly matches the observed l, s share in the OECD country-level data. The system of equations is separable by s, n, so that for each s, n there exists a set of $\mathcal{L} - 1$ equations to pin down $\mathcal{L} - 1$ free variables χ_{nls} (there is a free normalization to be made for

each n, s).[20]

I solve for equation (15) one country-sector n, s at a time and apply the following fixes for n, s-specific edge cases. Compared to the steps for the US and Mexico, there are two more edge cases (iii) and (iv) that can arise now that given the higher level of aggregation the ω_{njk} shares are not taken directly from the observed data:

(i) The country-specific data reports zero total investment for some asset category s: $\sum_l (P_{ns} I_{nls})_{OECD} = 0$. In other words, the shares $(\omega_{nls})_{OECD}$ on the RHS of equation (14) are undefined. In this case I set $\chi_{nls} = 1$, which corresponds to using pure theory-predicted apportioning shares ω_{njk}, which assumes that each sector j in country n uses capital services in the same relative proportions across k as the sector j in the USA. This edge case is the same as case (i) for Mexico.

(ii) The WIOD reports zero investment in a given aggregated sector s, so that $\sum_{k \in s} (P_{n,k} I_{n,k})_{\text{OECD}} = 0$. In other words, the shares on the LHS of equation (14) are undefined. This is not a problem as there is nothing to apportion. All final sector codes $k \in s$ must individually report zero investment supplied $(P_{n,s} I_{n,s} = 0)_{\text{WIOD}}$ in the WIOD data. This edge case is the same as case (ii) for the US and Mexico.

(iii) The components that make up the LHS numerator in equation (14), $\sum_{j \in l} \sum_{k \in s} \omega_{njk} (P_{n,k} I_{n,k})_{\text{OECD}}$ is equal to zero but the country-specific data on the RHS numerator is positive: $(P_{ns} I_{nls})_{OECD} > 0$. In this scenario, there is no value of $\chi_{n,ls}$ that could cause the two sides to match. If case (ii) is not true, i.e. the denominator is not zero, it must be that either $X_{n,j} = 0$ or $\beta^K_{USA,jk} = 0$ for each of $j \in l$ (recall the country-specific capital shares are winsorized and set to always be strictly positive, so $\beta^K_{nj} > 0$). If $X_{n,j} = 0$ (which applies only to two manufacturing sectors l in Luxembourg), I remove this l from the optimization program in equation (15), and set $\omega_{njk} = 0$ for all $j \in l$. Else, it must be that the US-specific capital coefficients are a poor proxy for this country n's capital coefficients. I then resort to applying the procedure in edge case (i) for the USA. I construct theory-predicted investment levels assuming that each sector j in country n uses capital services in the same relative proportions:

$$\widetilde{P_{n,k} I_{n,jk}}^{ss} \equiv \mu_{n,k} \beta^K_{n,j} X_{n,j},$$

where $\mu_{n,k}$ is the share of supplying sector k in total investments in country n. The actual value of $\mu_{n,k}$ is irrelevant because it cancels out of the expression for ω_{njk} (which is shares across j within k), just as it was irrelevant in case (i) for the USA. I then proceed to apply the optimization program in equation (15) to solve for χ for this specific country-sector n, s-pair.

(iv) The components that make up the LHS numerator in equation (14) are positive, $\sum_{j \in l} \sum_{k \in s} \omega_{njk} (P_{n,k} I_{n,k})_{\text{OECD}} > 0$ but the country-specific data on the RHS numerator is zero: $(P_{ns} I_{nls})_{OECD} = 0$. This is not a problem because setting $\chi_{n,ls} = 0$ will enable an exact solution to equation (15).

The steps described above apply to the following countries for which data exists in usable bilateral format from the OECD: Australia, Austria, Belgium, Canada, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Hungary, Italy, Japan, Lithuania, Luxembourg, Latvia, Netherlands, Poland, Portugal, Slovak Republic, Slovenia, and Sweden.

India. For India, data on gross fixed capital formation (GFCF) by asset by industry is available from the Ministry of Statistics and Programme Implementation. The data are available after 2012, so I apply the same

[20] For any other country satisfying the special case where $\mathcal{S} = \mathcal{K}$ and $\mathcal{L} = \mathcal{J}$ the procedure recovers exactly $\omega_{njk} = \frac{(P_{ns} I_{nls})_{OECD}}{\sum_l (P_{ns} I_{nls})_{OECD}}$, i.e. the same procedure that I apply to the US and Mexico.

steps as for Mexico above to backcast the flows in each of three years $t = 2012, 2013, 2014$ back to 1997 levels, which remedies any unequal growth over time in the size of each using industry. I take the average over the three years t of GFCF after backcasting as the effective value in 1997. I then generate similar concordances as with the set of countries in the OECD database to create the a supplying sector classification $\mathcal{K}$ and a using sector classification $\mathcal{L}$ specific to India that represents an aggregation of both the native Indian asset and activity codes and the definition of industries used in this paper. This yields a similar $\mathcal{L}_n \times \mathcal{S}_n$-level bilateral investment flows matrix (values of $P_{IND,s}I_{IND,ls}$), and from here on the same steps in the OECD case apply for computing $\omega_{IND,jk}$.

Korea. For Korea, equivalent data on bilateral gross fixed capital formation by type and by economic activities is published by the Bank of Korea and available since 2005. I apply the same steps as for India and Mexico above to backcast the flows in each of three years $t = 2005, 2006, 2007$ back to 1997 levels. I take the average over the three years t of GFCF after backcasting as the effective value in 1997. I also create a supplying sector classification $\mathcal{K}$ and a using sector classification $\mathcal{L}$ specific to Korea that represents an aggregation of both the native Korean asset and activity codes and the definition of industries used in this paper. This yields a similar $\mathcal{L}_n \times \mathcal{S}_n$-level bilateral investment flows matrix (values of $P_{KOR,s}I_{KOR,ls}$) for Korea, and from here on the same steps in the OECD case apply for computing $\omega_{KOR,jk}$.

Remaining Countries. I apply a simpler procedure for the remaining eleven countries in the WIOD for which data on bilateral GFCF by asset and by sector is completely unavailable. These countries are: Bulgaria, Brazil, China, Cyprus, Indonesia, Ireland, Malta, Romania, Russia, Turkey and Taiwan. I directly construct apportioning shares $\omega_{n,jk}$ as the theory-predicted steady-state share of investments in asset k made by sector j if each country n and the US used capital services in the same relative proportions:

$$\omega_{n,jk} \equiv \frac{\frac{\beta^K_{USA,jk}}{\sum_k \beta^K_{USA,jk}} \beta^K_{n,j} X_{nj}}{\sum_{j'} \frac{\beta^K_{USA,j'k}}{\sum_k \beta^K_{USA,j'k}} \beta^K_{nj'} X_{nj'}}.$$

These are the same as the 'alternative' apportioning shares constructed for the above countries in edge cases (where the country-specific information for a particular sector k is unavailable).

Other remarks. In principle variation across the supplying sector 's' dimension (shares across s within each l) can also be used to generate constraints, but such constraints cannot be satisfied with equality because of differences in reported ratios of final investment by asset across the WIOD and the country-specific sources. Because data in the WIOD are balanced to represent an internally consistent set of national accounts, I defer to data in the WIOD. Furthermore, the goal of the algorithm is to apportion observed expenditures at the supplying-sector-level in the WIOD data across using sectors, which suggests the need to identify ω_{njk} shares that sum to 1 over all j for each given k, rather than the other way around (which would only serve as a useful over-identification check on the WIOD data). Note also that the ω_{njk} are not directly used in the model anywhere. The ω_{njk} are only used to impute investment flows at the bilateral jk level given WIOD data on unilateral investment I_k, and thus satisfy all the adding-up constraints within the WIOD itself. It is possible that a sector is observed to invest more than its current value-added by capital. This is justifiable in the data given that investment is forward-looking and value-added is backwards looking. However, in the model the capital coefficients are always apportioned out of capital value-added so that a sector always has its rental payments on all assets k equal its total capital value-added.

A.3 Constructing matrix of capital service coefficients β^K

Given investment flows at the bilateral sector level, $P_{n,k}I_{n,jk}$ for each country n, I next compute normalized capital service coefficients using the steady-state relationship between rental payments on capital and new investment:

$$\gamma^K_{n,jk} = \frac{P_{n,k}I_{n,jk}\frac{r^f+\delta_k}{\delta_k}}{\sum_{k'} P_{n,k}I_{n,jk'}\frac{r^f+\delta_{n,k'}}{\delta_{k'}}}, \qquad \forall n, j, k.$$

and the unnormalized production coefficient on capital services from sector k (the elasticity of output q_{nj} with respect to κ_{njk}) is the normalized share multiplied into the overall capital value-added as a share of gross output:

$$\beta^K_{n,jk} = \gamma^K_{n,jk}\beta^K_{n,j}.$$

B Model and Calibration

B.1 Version of Economy in Autarky

In this sub-section I detail the autarky version of the economy nested by Proposition 1 and relate the impact of productivity shocks (the same ones considered in equation 10 in the open-economy) directly to welfare. In the special case of autarky, wages in each country can serve as the numeraire and there are no terms-of-trade effects. Corollary 2 derives exact analytical results for how productivity shocks ($\mathrm{d}\log A_j$) impact welfare (real per-period consumption, C), for a given country.

Corollary 2 (Productivity Shocks in Autarky) *Under autarky, the impact of unanticipated and permanent productivity shocks* $\mathrm{d}\log \boldsymbol{A}$ *on steady-state per-period welfare (final consumption C) in the economy is given by*

$$\mathrm{d}\log C = \boldsymbol{\alpha}'(\boldsymbol{I} - \boldsymbol{B})^{-1}\,\mathrm{d}\log \boldsymbol{A}, \tag{16}$$

where $\boldsymbol{\alpha}$ is a vector of preference coefficients over sectors, $\boldsymbol{I}$ is the identity matrix, and $\boldsymbol{B}$ is the $J \times J$ capital-augmented input-output matrix with coefficients $\boldsymbol{B}_{jk}$ given by the sum of sector j's output elasticities with respect to intermediate inputs and capital services from sector k:

$$\boldsymbol{B}_{jk} = \beta^M_{jk} + \beta^K_{jk}.$$

Proof. Because preferences and production are both Cobb-Douglas, sectoral allocations will not change in response to productivity shocks. That is, given L, the domestic market clearing condition renders sector output X_j a function of coefficients β and α, but not technology A. Household income consists of wage and capital income but the wage is the numeraire and capital income is the sum of a constant fraction of X_j in each sector 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 sector j facing a price P_k for intermediate inputs and a price r_k for capital services and a numeraire wage leads to unit costs (which equal prices P_j under perfect competition):

$$P_j = A_j^{-1}\left(\prod_k P_k^{\beta^M_{jk}} r_k^{\beta^K_{jk}}\right)\prod_k\left((\beta^M_{jk})^{-\beta^M_{jk}}(\beta^K_{jk})^{-\beta^K_{jk}}\right).$$

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

$$P_j = A_j^{-1} \left(\prod_k P_k^{\beta_{jk}^M + \beta_{jk}^K} \right) \eta_j, \tag{17}$$

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 (17) 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 Corollary 2

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

■

The term $\boldsymbol{\alpha}'(\boldsymbol{I} - \boldsymbol{B})^{-1}$ is a $1 \times K$ vector of sector-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). When capital services are modeled analogously to intermediate inputs in production, the extent of "roundabout production" increases. Just like static production network models, a similar Leontief inverse $(\boldsymbol{I} - \boldsymbol{B})^{-1}$ in equation (16) captures how shocks propagate. However, the matrix elements are augmented to include production coefficients on not only intermediate inputs (β_{jk}^M) but also capital services (β_{jk}^K).

This amplification result does not rely on there being multiple sectors in the economy. Take, for example, a one-sector economy (so $\alpha = 1$). Equation (16) simplifies to

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

where the scalar $B = \beta^M + \beta^K$ is the combined intermediate input and capital service share in production. For conventional values of cost-shares in production—intermediate inputs at 0.5, labor at 0.25, and capital services at 0.25, the elasticity of welfare to productivity is equal to 1/(1-0.75)=4. In comparison, the elasticity is halved at 1/(1-0.5)=2 in models where capital is treated as a primary factor.

Relation to Hulten (1978). In my model setting where capital services are used as flow inputs in production, Hulten's theorem no longer holds. Domar weights (sector 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 Corollary 2.

Corollary 3 (Domar Weights) *The $1 \times K$ vector of Domar weights, defined as sector 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

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

Proof. This comes directly from solving for sector output $\{X_j\}_j$ using the system of equations in Definition 1 applied to the case of autarky (setting $\pi = 0$ for $n \neq i$). In matrix form, these equations simplify to:

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

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

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

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

There are three reasons why Domar weights are no longer informative. The most obvious is that Corollary 2 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 real consumption C (real labor income and net capital income), whereas Hulten focuses on GDP, which (by definition) is the sum of labor income and *gross* capital income. This explains the adjustment by a factor of $\frac{L}{GDP}$ in the Domar weight. Finally, sector output in my model depends on demand for investment and final demand generated from net capital income. 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 limiting case where $r^f = 0$, all of capital value-added is re-invested. Since investment is counted as sector output, Domar weights contain the right information for the "input centrality" of each sector. The two measures of centrality coincide: $\boldsymbol{\Upsilon} = \boldsymbol{B}$. Domar weights as observed in the data (multiplied by $\frac{GDP}{L}$ to correct for the fact that the focus is on C, not GDP) would then act as sufficient statistics for computing the impact of productivity shocks on welfare. And of course, if capital plays no role in production ($\beta_{jk}^K = 0$), Hulten's result coincides with Corollary 2.

B.2 Model Calibration

Overview: treatment of capital across models. In the quantitative exercises, I benchmark the results in (i) my model to two alternative models: (ii) a static model with labor and capital as two fixed factors,

and (iii) a dynamic "aggregate-capital" model that assumes all sectors use different capital services k in the same relative proportions.

Model (iii) is for all practical purposes the same as the conventional multi-sector RBC model à la Long and Plosser (1983) and its recent extension to the global economy by Huo et al. (2023), where purchases of different types k of investment goods are aggregated into a single capital stock, the same composite capital is used in every sector j. In their model capital depreciates at a rate specific to the sector j of *use*. Model (iii) simplifies this by assuming that capital depreciates at the same rate everywhere. But this simplification is harmless—as long as capital is a composite, differences in depreciation at the using-sector j-level only act as a j-specific shifter of costs but does not change any of the counterfactuals.

There is yet another alternative to model (iii), which I will call model (iv) in this discussion. In model (iv), capital is disaggregated by supplying sector k, all using-sectors j use capital services k with the same relative intensities, but each type of capital asset k depreciates at its own rate, similar to the assumption in my model (i). There are two ways counterfactuals using model (iv) are different from model (iii).[21] First, different asset-specific depreciation rates increase the relative importance of slow-depreciating assets (these assets k will be calibrated to have higher γ^K_{jk}). Construction is long-lived, so in an impatient economy, investors demand a higher rate of return to make it worthwhile to invest in construction. Recall that

$$\gamma^K_{n,jk} = \frac{P_{n,k} I_{n,jk} \frac{r^f + \delta_k}{\delta_k}}{\sum_{k'} P_{n,k} I_{n,jk'} \frac{r^f + \delta_{n,k'}}{\delta_{k'}}}, \qquad \forall n, j, k,$$

so for a given amount of observed investment expenditures for a low-δ_k asset like construction, γ^K_{jk} will be higher. This force pushes gains from trade in this model to be lower than (iii) (more traded types of capital are shorter-lived). Second, preference coefficients in final demand in model (iv) are the same as my disaggregated-capital model (i) because investment is properly treated as its own category. To the extent that investment assets are more traded than $C + G$ in final demand, this force pushes gains from trade in this model to be higher than (iii). To save on space I have not reported results from this calibration but overall the quantitative results—gains from trade, propagation of shocks, etc—are slightly larger but not too different from model (iii), and still smaller than model (i), the fully-disaggregated case.

Production Expenditure Shares. I calibrate expenditure shares (output elasticities with respect to inputs) as simple shares of gross output. Intermediate input shares β^M_{ijk} are intermediate input expenditures by sector j on input k as a share of gross output. Labor shares β^L_{ij} are labor value-added as a share of gross output. Capital service coefficients β^K_{ijk} used in model calibration (i) are described Appendix Section A.3. The static model calibration (ii) treats capital as a factor in fixed supply and so I do not make use of k-level heterogeneity. Each using-sector has its overall capital intensity in gross output β^K_{ij} taken directly as capital value-added's share in gross output. In the aggregate-capital model calibration (iii), capital coefficients are constructed using each sector j's overall capital intensity apportioned over assets k in the same relative proportions in each sector j:

$$\beta^K_{njk} = \alpha_{nk} \beta^K_{nj},$$

[21] Foerster et al. (2022) have a similar discussion and label models (iii) and (iv) the "investment-aggregate" and the "capital-aggregate" model respectively (note: these are different from the names chosen in my paper). They mention that one advantage of the existing investment-aggregate (model iii) is that the dimensionality of the capital state vector remains low. However, due to my focus on steady-state outcomes, and unlike much of the existing RBC literature, I use an "exact-hat" method to solve for counterfactuals that circumvents this issue of dimensionality.

where α_{nk} denotes the share of goods from sector k in final demand (see the calibration of consumption expenditure shares).

A few papers have taken a different approach to calibrate production coefficients related to capital. Parro (2013) studies capital-skill complementarity in a model of trade with capital, but capital in his model depreciates fully within an accounting period. Similar to Alvarez and Lucas (2007), he calibrates all of value-added in the data as earnings by labor. His calibration differs in that his "capital coefficients" in production are taken from intermediate use shares for goods that are predominantly imported as capital. In both these papers, the degree of roundaboutness in production is identical to a standard input-output model with only intermediates.

The approach taken in my paper assumes that, for any given sector, countries operate different production functions. Production coefficients $\boldsymbol{\beta}$ vary across countries within each sector. This is important for the comparative-advantage-based mechanism. Trade liberalization affects countries differentially—the more capital-intensive countries gain market share within each sector. This assumption is supported by the data where countries operate with different expenditure shares in production. Part of the reason why countries like Korea only have a capital-intensity of 11 percent and Mexico 37 percent can be due to differences in accounting conventions. My approach integrates the supply-use of both intermediate inputs and capital services, and therefore captures the full extent to which countries use inputs from supplying sectors.

Consumption Expenditure Shares. There exist three final consumption categories (columns in the standard input-output tables): (i) C, by households, (ii) I, investment for gross fixed capital formation, and (iii) G, by the government.[22] According to the System of National Accounts, household purchases of durable investment goods such as autos count under household consumption rather than gross fixed capital formation. This is consistent with my model and calibration. To my knowledge the WIOD data abides by this convention.

For calibrating the main disaggregated-capital model (i), I compute demand-side Cobb-Douglas preference weights α_{nk} across supplying sectors k using:

$$\alpha_{nk} \equiv \frac{C_k + G_k}{\sum_{k'} C_{k'} + G_{k'}}.$$

For models (ii) and (iii) I compute demand-side Cobb-Douglas preference weights α_{nk} across supplying sectors k by using:

$$\alpha_{nk} \equiv \frac{C_k + I_k + G_k}{\sum_{k'} C_{k'} + I_{k'} + G_{k'}}.$$

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 sectors 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 sector 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. Table A.1 reports the trade elasticities I use by sector.

[22]Change in inventories and net exports also exist as "final-use" columns in the input-output tables but this is misleading because they are an adjustment to make expenditures add back up to total output for a given row. Each other column in the input-output table for a given row (a given producing sector-country) refers to expenditures including the portion that was drawn down from inventories and including imports. Ignoring change in inventories and net exports columns is therefore consistent from an expenditure point of view.

Depreciation Rates. I assume that a given type of capital asset k depreciates at the same rate regardless of the country n or sector 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 27-sector classification in the paper. Whenever there are multiple assets that map into an sector, I take the average depreciation rate among those assets. Some sectors (such as agriculture and various professional services) in my classification do not match to any available asset type in the BEA publication. I set the depreciation rates for assets produced by these sectors as follows. I assume assets from the real estate and construction sectors depreciate at the same rate (0.03). I assume that assets produced by the management and administrative support industries depreciate at rate 0.33 (the average of the depreciation of ICT, R&D, brand equity and firm-specific resources in Corrado et al., 2009). I set the depreciation rate of assets in remaining sectors to equal 0.16, the average in the sample.

Trade Deficits. I do not read deficits and output directly from the data to avoid generating several inconsistencies with the assumptions in the model. First, the model assumes that the global 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 sector'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 (see above), 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 (see above). 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.

Instead, I solve for the deficits in each country that rationalize the other calibrated parameters. Specifically, under Definition 1, 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). Solving this system of equations yields model-implied values of D_n and X_{ij} that could technically differ from observed values in the standard input-output table.

Despite these differences, I find that the correlation between deficits (ratios of expenditures to income) in the data and in the model, $\left\{ \frac{w_n L_n + D_n}{w_n L_n} \right\}_n$, is 0.71. The correlation between log output $\log(X_{ik})$ in the data and in the model is 0.99.

C Quantitative Results

C.1 Proofs

Proof of Proposition 1: Counterfactuals in the Global Steady State. These expressions come directly from relating the definition of the open economy steady state (Definition 1) 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}. The first two conditions come directly from the corresponding expressions in Definition 1. 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 equation (6). The forth expression comes from applying hat algebra to the unit cost Cobb-Douglas function in equation (5), and the fifth expression comes from a similar hat algebra application to the unit consumption price index of industry k in country n in equation (4):

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

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Proof of Corollary 1: Gains from international trade. The easiest way to compute this is to leverage Proposition 1 and set $\hat{\tau}_{nij} = \infty$ for all j and all $n \neq i$, and remove imbalances $\hat{D}_n D_n = 0$ for all n. Given the Cobb-Douglas production functions everywhere, the price and income impacts behind the expression for the welfare change in equation (11) can be solved separately. It is convenient to choose wage in country n to be the numeraire, so there are no changes in labor incomes. First, the change in the sectoral price index, following the fifth condition in Proposition 1, is

$$\hat{P}_{nk}^{-\theta_k} = \pi_{nnk}\hat{c}_{ik}^{-\theta_k},$$

and using the expression for $\hat{c}_{ij}$ in the fourth condition in Proposition 1, can be written as

$$\hat{P}_{nj} = \pi_{nnj}^{-\frac{1}{\theta_j}}\prod_k \hat{P}_{nk}^{\beta^M_{njk}+\beta^K_{njk}}.$$

Taking the Leontief inverse and letting $\tilde{\beta}_{njk}$ denote jk elements of the matrix $(\boldsymbol{I} - \boldsymbol{B}^M_n - \boldsymbol{B}^K_n)^{-1}$ yields

$$\hat{P}_{nj} = \prod_k \pi_{nnk}^{-\frac{\tilde{\beta}_{njk}}{\theta_k}},$$

and the price index dual to household consumption is

$$\hat{P}_n = \prod_{j,k} \pi_{nnk}^{-\frac{\tilde{\beta}_{njk}\alpha_{nj}}{\theta_k}}.$$

Second, the change in net capital incomes can be solved using the second goods market clearing condition

in Proposition 1, which under a return to autarky simplifies to:

$$X'_{nj} = \sum_k \left(\beta^M_{nkj} + \frac{\delta_{nj}}{r^f_n + \delta_{nj}} \beta^K_{nkj} \right) X'_{nk} + \alpha_{nj} \left(w_n L_n + \sum_j \sum_k \frac{r^f_n}{r^f_n + \delta_{nj}} \beta^K_{nkj} X'_{nk} \right),$$

and again, using matrix algebra, the solution for X'_{nj} can be expressed as

$$\boldsymbol{X}'_n = (\boldsymbol{I} - \boldsymbol{S}_n)^{-1} \boldsymbol{Y}^L_n,$$

where $\boldsymbol{Y}$ is an observable $\mathcal{K}$-vector of sectoral consumption out of labor income $Y^L_{nj} \equiv \alpha_{nj} w_n L_n$, and $\boldsymbol{S}_n$ is a $\mathcal{K} \times \mathcal{K}$-matrix of capital-adjusted supply coefficients with elements given by a function over model parameters

$$S_{njk} \equiv \beta^M_{nkj} + \frac{\delta_{nj}}{r^f_n + \delta_{nj}} \beta^K_{nkj} + \alpha_{nj} \left(\sum_{j'} \frac{r^f_n}{r^f_n + \delta_{nj}} \beta_{nkj} \right),$$

Given values of X'_{nj} it is easy to find $\hat{X}_{nj}$ and then equation (12) follows from the definition of $\hat{C}$ in equation (11) and the definition of the gains from international trade (relative to autarky) in Costinot and Rodríguez-Clare (2014):

$$GFT_n \equiv 1 - \frac{C^{\text{autarky}}_n}{C_n}.$$

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C.2 Propagation of Productivity Shocks

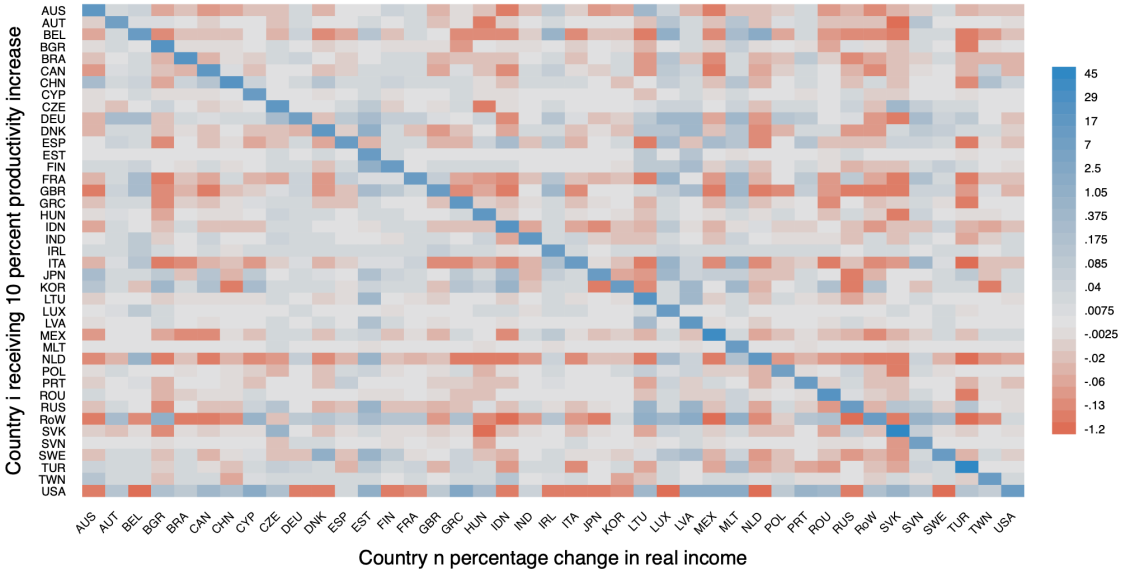
Figures C.1 and C.2 display how the propagation matrices shown in Figure 7 in the main text compare to the two alternative model calibrations: (ii) a static model, and (iii) a dynamic aggregate-capital model. Instead of reproducing the propagation matrices under the two alternative calibrations, which are hard to compare, I plot heatmaps of the *difference* in the value of each cell between model (i) and either of model (ii) and (iii). Positive numbers imply that model (i) has a higher elasticity.

Figure C.1 panel (a) shows that compared to the static model, the disaggregated-capital model generates higher own-country elasticities of welfare to productivity shocks, and more pronounced winners and losers. Panel (b) shows that propagation of sectoral shocks is everywhere weakly stronger: price indices fall by more in every sector when capital is endogenous.

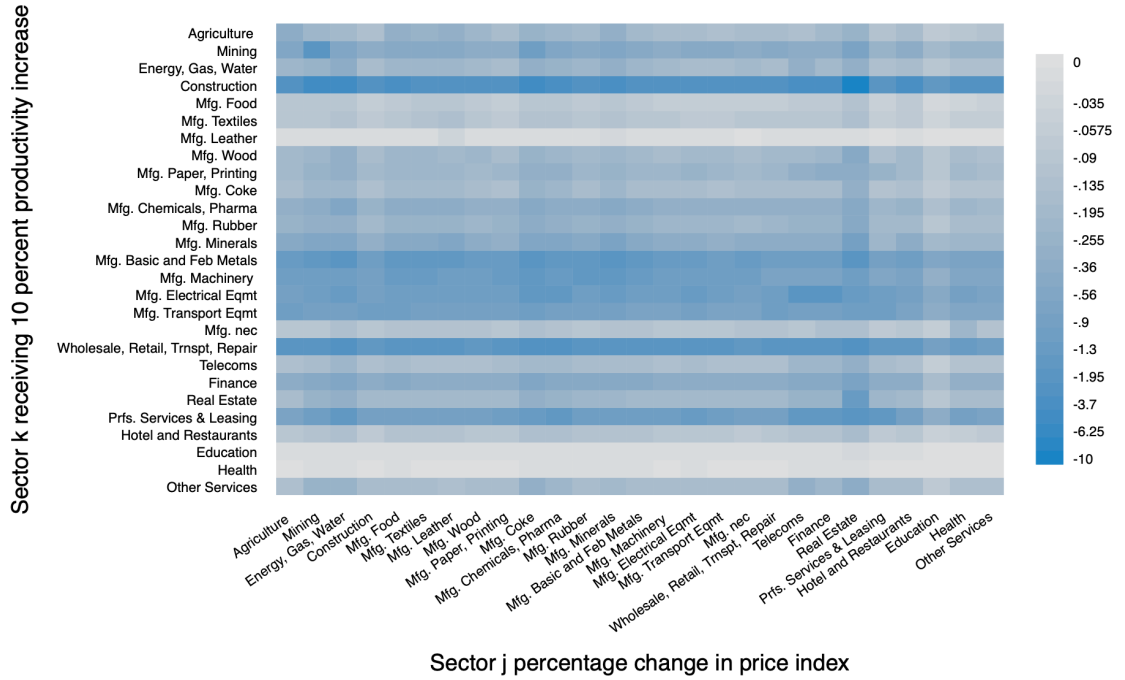
Figure C.2 panel (a) shows that compared to the aggregate-capital model, the disaggregated-capital model generates on average higher own-country elasticities and on average lower (more negative) cross-country elasticities. The terms-of-trade effects from output reallocation are larger when capital is disaggregated and a country-wide productivity shock occurs. This generally works to the benefit of the recipient country and to the detriment of others. Panel (b) shows that sectoral propagation is higher for some sectors and lower for other sectors. Productivity shocks in capital-supplying sectors like construction, machinery, electrical equipment, transport equipment, as well as professional services and leasing have more negative (beneficial) price impacts under the disaggregated-capital model. In comparison the aggregate-capital model misses this heterogeneity and ascribes a more negative (beneficial) price impact to sectors like healthcare, education, agriculture, which are all (assumed) to make up the composite capital good.

Figure C.1: Propagation of Productivity Shocks across Countries and Sectors
Difference between model (i) and model (ii) static calibration

(a) Impact of Productivity Shock in Country i on Real Income in Country n



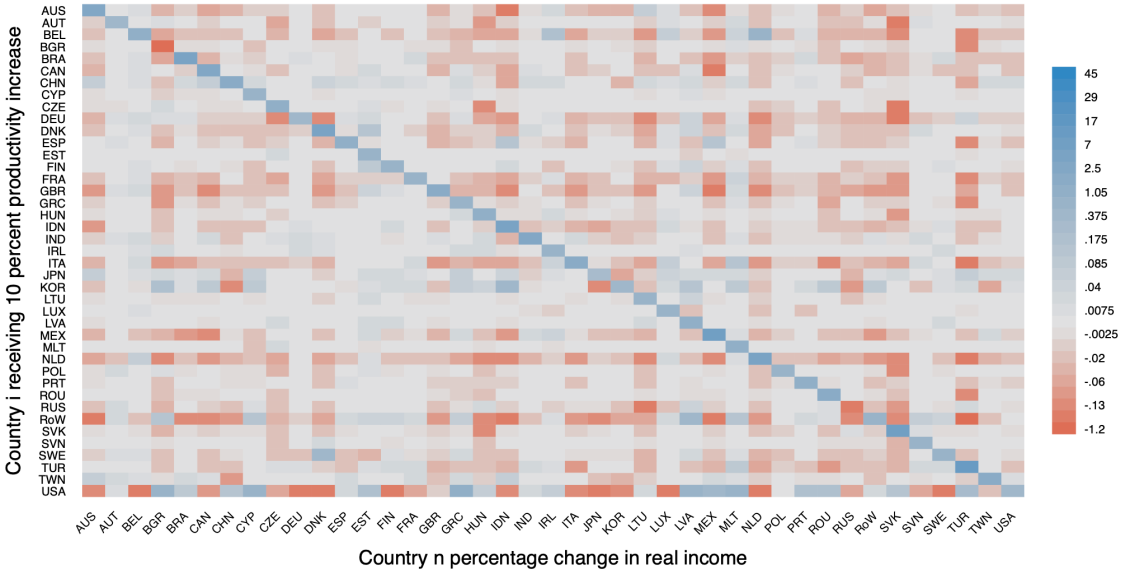
(b) Impact of Productivity Shock in Sector k on the Price Index in Sector j



Notes: Panel (a) of this figure plots the difference between the (i) disaggregated-capital and (ii) static model in the impact of a 10 percent uniform productivity shock in each given country i on real income in country n. The change in real income is measured using equation (11). Panel (b) of this figure plots the same model (i) versus (ii) difference in the impact of a 10 percent productivity shock in each given sector k on the average price index in sector j (averaged using country-consumption as weights).

Figure C.2: Propagation of Productivity Shocks across Countries and Sectors
Difference between model (i) and model (iii) aggregate-capital calibration

(a) Impact of Productivity Shock in Country i on Real Income in Country n



(b) Impact of Productivity Shock in Sector k on the Price Index in Sector j



Notes: Panel (a) of this figure plots the difference between the (i) disaggregated-capital and (iii) aggregate-capital model in the impact of a 10 percent uniform productivity shock in each given country i on real income in country n. The change in real income is measured using equation (11). Panel (b) of this figure plots the same model (i) versus (iii) difference in the impact of a 10 percent productivity shock in each given sector k on the average price index in sector j (averaged using country-consumption as weights).

C.3 Welfare

Return to Autarky. I use equation (12) to compute the gains from trade under the disaggregated-capital and aggregated-capital models. These two models share exactly the same equilibrium conditions and differ only in terms of their production-side capital coefficients β^K_{njk} and consumption coefficients α_{nj}. For the static model, it is easy to re-trace the steps in the proof of Corollary 1 to show that the gains from trade formula can be altered as follows:

$$GFT_n^{(\text{static})} = 1 - \prod_{j,k} \pi_{nnk}^{\frac{\tilde{\beta}_{njk}\alpha_{nj}}{\theta_j}} \left(1 + (1 - s_n^L)(\hat{R}_n - 1)\right) \hat{R}_n^{-\sum_{j,k}\beta^K_{nk}\tilde{\beta}_{njk}\alpha_{nj}},$$

where $\tilde{\boldsymbol{\beta}}$ is the Leontief inverse of the standard input-output matrix containing only intermediate coefficients $\boldsymbol{\beta^M}$. Since capital is a fixed factor, the change in net capital income, $\hat{R}$ is the change in total capital income, which is also the change in the rental price of capital,

$$\hat{R}_n = \hat{r}_n = \frac{\sum_k \beta^K_{ik} X'_{ik}}{\sum_k \beta^K_{ik} X_{ik}},$$

and X'_{ik} can be computed using a similar Leontief inverse as the other two models:

$$\boldsymbol{X}'_n = (\boldsymbol{I} - \boldsymbol{S}_n)^{-1}\boldsymbol{Y}^L_n,$$

where $\boldsymbol{Y}$ is an observable $\mathcal{K}$-vector of sectoral consumption out of labor income $Y^L_{nj} \equiv \alpha_{nj} w_n L_n$, and $\boldsymbol{S}_n$ is a $\mathcal{K} \times \mathcal{K}$-matrix of capital-adjusted supply coefficients with elements given by a function over model parameters

$$S_{njk} \equiv \beta^M_{nkj} + \alpha_{nj}\beta_{nk}.$$

Expenditures versus Income. To compute welfare changes in steady state given by equation (11), note that real income used for consumption is the sum of labor and net capital income divided by the final consumption price index. Therefore

$$C_n \equiv \frac{w_n L_n + \sum_j \sum_k \frac{r^f_n}{r^f_n + \delta_j} \beta^K_{nkj} X_{nk}}{\prod_k P_{nk}^{\alpha_{nk}}}$$

and setting $\hat{C}_n = \frac{C'_n}{C_n}$ yields the expression for the change in welfare in equation (11).

The definition of welfare is real income used for consumption (in equation 11). This definition does not include consumption out of net transfers of deficits (exogenous values of D_n). The following provides an

alternative derivation for welfare based on final consumption *expenditures* rather than income:

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

$$= s_n^L \cdot \underbrace{\frac{\hat{w}_n \hat{L}_n}{\prod_k \hat{P}_{nk}^{\alpha_{nk}}}}_{\Delta\text{real labor income}} + s_n^K \cdot \underbrace{\frac{\sum_k \mu_{nk} \hat{X}_{nk}}{\prod_k \hat{P}_{nk}^{\alpha_{nk}}}}_{\Delta\text{real net capital income}} + s_n^D \cdot \underbrace{\frac{\hat{D}_n}{\prod_k \hat{P}_{nk}^{\alpha_{nk}}}}_{\Delta\text{real deficit transfers}}, \tag{18}$$

where μ_{nk} denotes country n's share of net capital income from sector k:

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

and s_n^L, s_n^K, s_n^D denotes country n's share of total final consumption expenditures out of labor income, net capital income, and deficits, respectively, e.g.

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

In practice, because deficits are constant across counterfactuals and a small initial share of total consumption expenditures, it matters little for the quantitative results whether I define welfare using the expenditure-based derivation above or the income-based derivation in the main text.

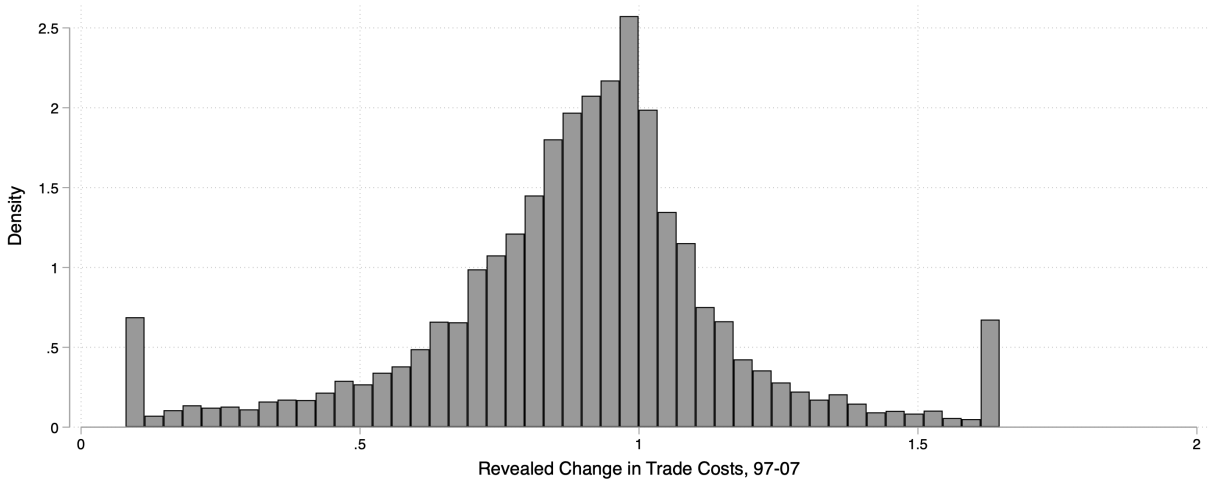
C.4 Head-Ries Revealed Trade Costs

I use similar symmetry assumption as Head and Ries (2001) to isolate the changes in bilateral trade costs between 1997 and 2007 in the data. Assuming trade cost changes are symmetric, and that domestic trade costs in each region did not change, I compute the change in trade costs as:

$$\hat{\tau}_{nij}^{97 \to 07} = \hat{\tau}_{inj}^{97 \to 07} = \left(\frac{\hat{\pi}_{nij} \hat{\pi}_{inj}}{\hat{\pi}_{nnj} \hat{\pi}_{iij}} \right)^{-\frac{1}{2\theta_j}},$$

I winsorize the inferred $\hat{\tau}_{nij}^{97 \to 07}$ at the 97.5 and 2.5 percentiles. Figure C.3 plots the distribution of trade cost changes over this period. While on average trade costs have fallen, imputed trade costs rose for 31 percent of bilateral links. This occurs because, as explained in the main text, the benchmarking assumption isolates changes in international trade frictions above and beyond any changes in domestic trade frictions. Any common shocks that affect all international and domestic trade routes are indeed inseparable from general productivity shocks and thus not the focus of this exercise.

Figure C.3: Distribution of Revealed Changes in Trade Costs, $\hat{\tau}_{nij}^{97\to07}$



Notes: This figure plots the distribution of the revealed changes in trade costs using WIOD data in 1997 and 2007.