How Do Endowments Determine Trade? Quantifying the Output Mix, Factor Price and Skill-Biased Technology Channels[*]

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ABSTRACT:

Differences in how countries absorb their endowments of skilled and unskilled labour can be decomposed into (*1a*) between-industry differences in output mix and (*1b*) within-industry differences in skill intensities. The latter can be decomposed into contributions from cross-country differences in (*2a*) relative wages and (*2b*) skill-biased factor-augmenting technologies. To investigate the relative importance of each, we develop a multi-sector Eaton-Kortum model featuring skilled labour, unskilled labour and factor-augmenting international technology differences. The model is calibrated to WIOD data for 39 countries in 2006. We use a model-based decomposition to show that the skill-intensity mechanism is much more important than the output-mix mechanism. Further, differences in skill intensities across countries are explained in similar proportions by the relative-wage mechanism and the technology mechanism. We show that these model-based results have strong counterparts in the data. Our results have immediate implications for the impact of endowments and skill-biased technology on output mix, trade in goods, trade in factor services, and international differences in factor prices and skill premia.

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1. Introduction

Two major themes dominate the vast literature on how endowments affect international trade and domestic wages. Stated as decompositions, these themes are:

1. Differences in how countries absorb their endowments of skilled and unskilled labour can be decomposed into (*a*) between-industry differences in output mix and (*b*) within-industry differences in skill intensities.
2. Within each industry, cross-country differences in skill intensities can be decomposed into contributions from cross-country differences in (*a*) relative wages and (*b*) skill-biased, factor-augmenting technology.

Many questions in the trade literature are fundamentally about the relative importance of the terms in these two decompositions. Most obviously, the impact of endowments on goods trade is likely big when 1*a* is large relative to 1*b* (e.g.,Romalis, 2004, Chor, 2010) and the effect of exogenous changes in factor supplies on wages can be muted by these output-mix responses as well e.g., Burstein, Hanson, Tian and Vogel (2020). The wage impacts of migration-induced endowment shifts can also be offset by the skill upgrading of 2*b* e.g., Gandal, Hanson and Slaughter (2004) and Dustmann and Glitz (2015). Trefler (1993, 1995) and Davis and Weinstein (2001) offer competing views to what degree the failure of the Heckscher-Ohlin-Vanek factor content prediction is due to departures from factor price equalization (2*a*), factor-augmenting international technology differences (2*b*), or trade costs.

Despite the well-known importance of these two decompositions and the many excellent country-level studies of them that we review below, an important addition to our stock of knowledge would be a cross-country study of the decompositions within a unified framework. Such an exercise faces two challenges. First, a key component of the decompositions is wages, but these are endogenous so that a general equilibrium model is needed. To endogenize wages we set up a multi-factor, multi-sector Eaton and Kortum (2002) model featuring the interindustry linkages of Caliendo and Parro (2015) and CES substitution possibilities between skilled and unskilled labour as in Parro (2013) and Burstein and Vogel (2017). Second, while there are various ways of estimating factor-augmenting international technology differences (Caselli and Coleman, 2006, Trefler, 1993, Malmberg, 2017), none of these is consistent with our model.[1] We therefore develop a new method of estimating factor-augmenting international technology differences. We calibrate the model using WIOD data (Timmer, Dietzenbacher, Los, Stehrer and Vries, 2015) for 39 countries and 23 industries in 2006. The model provides a unified framework for our two decompositions.

Since estimates of factor-augmenting technology are central to our results, we briefly discuss and compare them to a previous estimate. Let λ_{Si}^{V} and λ_{Ui}^{V} be the productivities of skilled and unskilled labour in country i. These are our key factor-augmenting technology parameters. We develop a model-consistent estimator of the $\lambda_{Si}^{V}/\lambda_{Ui}^{V}$ that in essence is a function of the ratio of skilled to unskilled labour employed in each industry and country and country-specific skill

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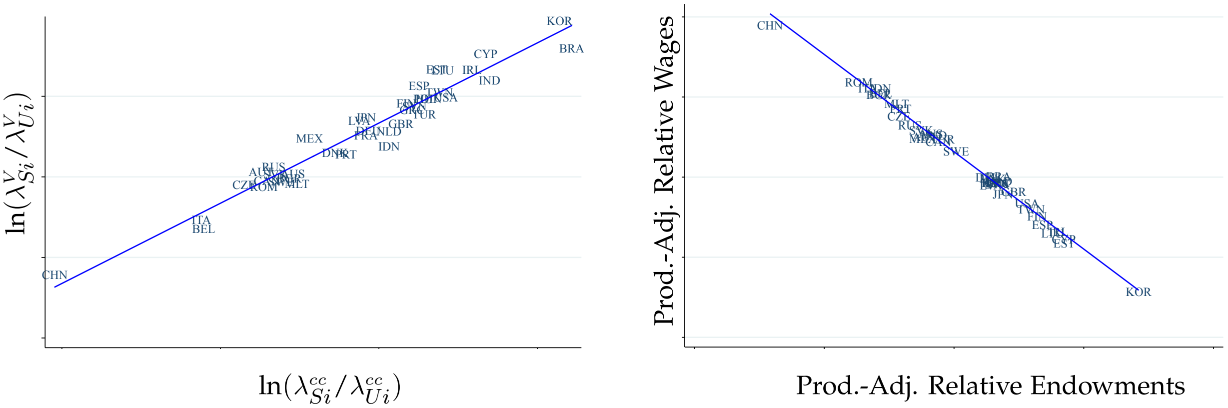
[1] E.g., Caselli and Coleman use an aggregate production function and Malmberg has no intermediate inputs.

Figure 1: Endowments, Technology and Wages



Notes: The left panel plots our estimates of $\lambda^V_{Si}/\lambda^V_{Ui}$ (vertical axis) against $\lambda^V_{Si}/\lambda^V_{Ui}$ calculated using the Caselli and Coleman (2006) method (horizontal axis). The right panel plots relative wages $w_{Si}\lambda^V_{Ui}/w_{Ui}\lambda^V_{Si}$ against relative endowments $V_{Si}\lambda^V_{Si}/V_{Ui}\lambda^V_{Ui}$, each in productivity-adjusted units. Lines in both graphs are OLS best fits. Each data point is a country in both graphs.

premia. However, the analysis is more complicated than this because of the presence of many industries as well as Ricardian technology parameters which must also be estimated. To check that our estimates of $\lambda^V_{Si}/\lambda^V_{Ui}$ are sensible we compare them to the $\lambda^V_{Si}/\lambda^V_{Ui}$ calculated using the single-sector method of Caselli and Coleman (2006). The left panel of figure 1 plots our $\lambda^V_{Si}/\lambda^V_{Ui}$ (vertical axis) against the Caselli-Coleman $\lambda^{cc}_{Si}/\lambda^{cc}_{Ui}$ (horizontal axis). They are very similar, which is at once both surprising and reassuring, as we discuss in section 5.

Having calibrated our model we turn to our first decomposition. We use the quantitative model to trace out the impact of a change in endowments on (1*a*) between-industry output mix and (1*b*) within-industry skill intensities. Specifically, we consider the following thought experiment: If we eliminate endowments-based comparative advantage by judiciously redistributing endowments across countries, what share of these endowment changes would be absorbed by between-industry shifts in output versus within-industry shifts in skill intensities? We find that for all countries, output mix plays a small role in absorbing the redistributed endowments: On average, output mix accounts for only 4% of the decomposition and skill intensity accounts for the remaining 96%. In short, the output-mix channel is only a small part of the adjustment mechanism. In our literature review, we document that this stark result appears in many (though not all) individual-country studies on the effects of migration.

Our result raises two issues. First, does it conflict with existing evidence of Rybczynski and Heckscher-Ohlin effects e.g., Baldwin (1971), Romalis (2004), Chor (2010), and Morrow (2010)? The answer is no. When we run regressions based on Romalis (2004) using our data, we replicate his findings. This points to the distinction between (*i*) observing that output-mix changes have the *direction* predicted by our theories and (*ii*) finding that these changes are important in *magnitude* for how countries absorb their endowments.

Second, is our decomposition driven by the model or the data? We provide strong evidence that it is driven by the data. The right panel of figure 1 plots raw data on the productivity-adjusted wage of skilled relative to unskilled labour against the productivity-adjusted endowment of skilled relative to unskilled labour. We show that if the data are consistent with the model then the figure 1 data plot must exhibit two features. First, the slope must equal the inverse of the elasticity of substitution between skilled and unskilled labour. The inverse of the estimated slope is 1.64, which is in the tight 1.6–1.8 range favoured by Acemoglu and Autor (2011, p. 1107–1109). Second, deviations from the line are proportional to the contribution of output mix to the absorption of endowments. The figure 1 deviations from the line are tiny, which means that the output-mix channel is small relative to the skill-intensity channel. It thus appears that our model-based conclusions are driven by features of the data.

We next turn to our second decomposition, that is, decomposing cross-country skill-intensity differences into contributions from cross-country wage differences and factor-augmenting international technology differences. In the raw data, roughly 38% of the variance in skill intensities is explained by variation in wages (2*a*) and 25% of the variance is explained by variation in technology (2*b*).[2] In short, the wage and technology components of the decomposition are similiarly important and together explain roughly half of the variance.

The limitation of the above use of raw data for the decomposition is that it treats wages exogenously when in fact they are endogenously determined in part by factor-augmenting technology. Therefore, we may be attributing to wages what in general equilibrium should be attributed to technology. We therefore use the quantitative model to revisit the decomposition. We consider the thought experiment of 'switching off' the technology parameters by setting the $\lambda^V_{Si}/\lambda^V_{Ui}$ to unity in all countries. The impact on productivity-adjusted skill intensities is large — the log change in skill intensity has a variance of 0.43.[3] This 0.43 decomposes into a positive *direct effect* of switching off the $\lambda^V_{Si}/\lambda^V_{Ui}$ and a negative *indirect effect* operating via general equilibrium changes to wages and product prices. Because the effects are offsetting, the direct effect must account for more than 100% of the decomposition. We find that the direct technology effect is 289% (mechanism 2*b*), while the indirect wage effect is –189% (mechanism 2*a*). This means that both mechanisms are important when thinking about the effect of technology differences on input techniques in general equilibrium, a point previously under-developed in the vast Heckscher-Ohlin literature.

While the $\lambda^V_{Si}/\lambda^V_{Ui}$ are important for our decompositions, it would be good to establish their importance more generally. To this end, we compare the role of the $\lambda^V_{Si}/\lambda^V_{Ui}$ to the role of the Ricardian technology parameters, parameters that has been documented as important in the past e.g., Costinot, Donaldson and Komunjer (2012). Specifically, we compare the effects of switching off the $\lambda^V_{Si}/\lambda^V_{Ui}$ with the effects of switching off the Ricardian technology parameters on equilibrium unit input requirements. When we do this, we find that the two sets of technology parameters have comparable counterfactual power. Hence, our emphasis on factor-augmenting technologies is appropriate in terms of being quantitatively important.

Our decomposition of skill intensities into wages and technology bears directly on an older

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[2] The remaining variance cannot be explained by Ricardian technology. Skilled and unskilled input requirements depend on Ricardian technology parameters, but the ratio of input requirements (skill intensities) do not.

[3] For comparison, the mean within-industry variance across countries is 0.59.

debate about the failure of the Heckscher-Ohlin-Vanek factor content of trade prediction. While there are many explanations for its failure, two prominent ones are departures from factor price equalization and factor augmenting productivity differences.[4] Davis and Weinstein (2001) point to the failure of factor price equalization and arrive at this conclusion by showing that international differences in factor intensities are driven by international differences in factor prices. In contrast, Trefler (1993) points to international differences in factor-augmenting technology and arrives at this conclusion by considering productivity-adjusted skill intensities. Our decomposition of skill intensities shows that factor prices and factor-augmenting technology are *both* important. It follows that Davis and Weinstein and Trefler were both right, but that each had only a partial picture of the problem. We are able to show this because of advances in quantitative modelling that were not available to these researchers. We close by asking whether taking these two factors into account is enough to rescue the Vanek equation. The answer is "not quite": Even after taking these into account, there is still missing trade that we then unpack using our quantitative model.

Literature Review

Our paper is most closely related to research which attaches skilled and unskilled labour to a multi-sector Eaton-Kortum model. See especially Parro (2013), Caron, Fally and Markusen (2014), Burstein, Cravino and Vogel (2013), and Burstein and Vogel (2017). These papers are largely concerned with the impact of falling trade costs on the skill premium. In contrast, our interest in the skill premium is not as an outcome to be explained but as one of several channels through which economies adjust to their endowments.[5]

A large literature on the impact of migration on US states and cities finds that output-mix adjustments play only a small role in absorbing changes in factor supply. Card and Lewis (2007) find that in response to unskilled Mexican migration, most cities did not experience either output-mix or relative wage changes. They did experience skill-intensity changes, but the authors do not investigate whether or not this is due to skill-biased technology adoption. Lewis (2004) examines the impact of the Mariel boat lift and Gandal et al. (2004) examine the impact of Russian immigration to Israel. Both find that the immigration did not cause changes in output mix, but did accompany differential adoption of factor-biased technologies. Two studies that exploit

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[4] A full list of supply-side explanations includes Hicks-neutral international productivity differences (e.g., Trefler, 1995, Debaere, 2003), Ricardian productivity differences (e.g., Marshall, 2012, but not Nishioka, 2012), factor-augmenting productivity differences (e.g., Trefler, 1993), factor prices (e.g., Fadinger, 2011) and trade costs (e.g., Staiger, Deardorff and Stern, 1987). Davis and Weinstein (2001) are unique in ambitiously considering all of these determinants, excluding factor-augmenting productivity differences.

[5] Parro (2013) examines the impact of trade in capital goods on the skill premium. He considers a third factor (capital) which complements skilled labour and thus influences the skill premium. He provides a model-based decomposition of the skill premium and finds that trade in capital goods has important impacts on inequality. Burstein et al. (2013) is closely related to Parro (2013), but of less relevance here given our interest in endowments-based comparative advantage because they assume that factor intensities are the same across industries. Burstein and Vogel (2017) introduce trade-induced directed technical change. They allow for within-industry firm heterogeneity in which more productive firms use more skill-intensive techniques. They then examine the impact of trade and technical change on the skill premium. Again, this is not our primary focus. Importantly, they allow the skill-bias of technology to adjust endogenously (due to selection effects) whereas we treat technology as exogenous. Our evidence strongly supports their research direction. Caron et al. (2014) is primarily concerned with non-homothetic preferences as a source of comparative advantage.

immigration impacts on US states and commuting zones are Hanson and Slaughter (2002) and Burstein et al. (2020). Both find evidence of substantial output-mix effects, especially for tradable industries and occupations, respectively. The latter also find that price movements are important for nontradable sectors. In our cross-country setting (as opposed to the above cross-state or cross-commuting zone setting) we expect very low levels of mobility/migration and very weak pressures for factor price equalization, so we expect our results to have weaker output-mix effects.

Other parts of the international trade literature place less of an emphasis on the effect of changes in factor supply *per se*, and focus more on how output composition changes in response to trade liberalization. While factor endowment based trade theories predict strong reallocations across sectors following trade reforms, Goldberg and Pavcnik (2007) document little evidence in support of such reallocation.[6] Parro (2013) uses a structural model to estimate the effect of a reduction in bilateral trade costs on the skill premium using a canonical factor endowments model and finds that the magnitudes of the resulting changes are very close to zero, which reflects a small amount of increased specialization across sectors.

Finally, our paper is related to another literature on structural estimation of the the world matrix of direct requirements of primary factors ($\mathbf{D}$) and the world input-output matrix of direct requirements of intermediate inputs ($\mathbf{B}$). The existing Heckscher-Ohlin-Vanek (HOV) literature has not taken a structural approach to estimating $\mathbf{D}$ and $\mathbf{B}$: Trefler (1995) estimates $\mathbf{D}$, Davis and Weinstein (2001) estimate $\mathbf{D}(\mathbf{I}-\mathbf{B})^{-1}$, and neither uses prices for this estimation. More recently, Caliendo, Parro and Tsyvinski (2017) and Antràs and de Gortari (2017) structurally estimate $\mathbf{B}$ using prices and taking into account price endogeneity. We structurally estimate $\mathbf{D}$ and $\mathbf{B}$ as functions of endogenous prices and productivity parameters.

Outline

Section 2 begins by discussing a fundamental identification problem encountered when one tries to identify factor augmenting productivity using data on skill intensity and skill premia. Section 3 presents our model. Section 4 describes our data and strategy for calibrating the parameters of the model. Section 5 presents data-based evidence for the first of our decompositions: how countries absorb differences in endowments. Section 6 presents similar evidence using model-based counterfactuals. Section 7 presents model-based evidence for the second of our decompositions: how skill intensities decompose into wages and technology. Section 8 discusses the implications of our results for tests of the fit of the Heckscher-Ohlin-Vanek equation. Section 9 concludes.

2. Identification

Disentangling substitution effects (mechanism *2a*) from factor-augmenting international technology differences (mechanism *2b*) raises an identification issue documented by Diamond, McFadden and Rodriguez (1978), but ignored in the trade-and-endowments literature. Consider the

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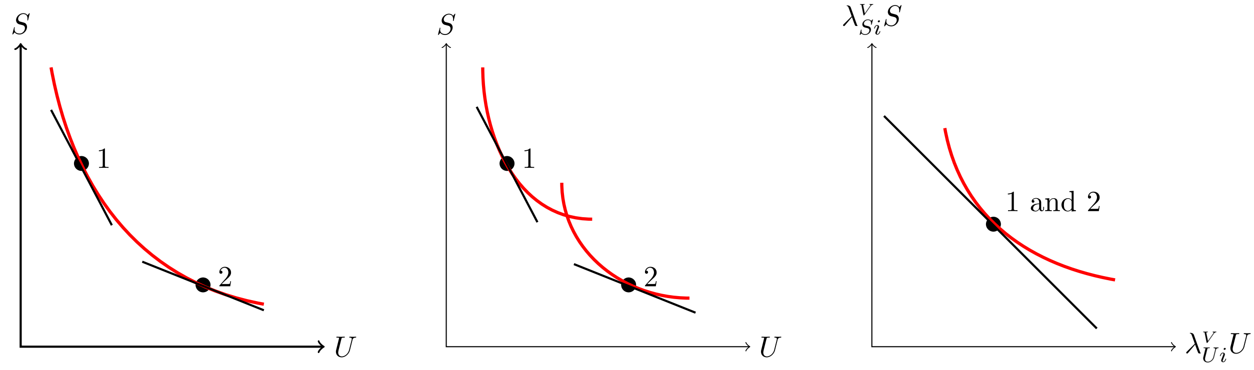
[6] Specifically, they cite studies by Revenga (1997), Hanson and Harrison (1999), and Feliciano (2001) for Mexico; by Attanasio, Goldberg and Pavcnik (2004) for Colombia; by Currie and Harrison (1997) for Morocco; by Topalova (2010) for India; and by Wacziarg and Wallack (2004) in a cross-country comparison.

Figure 2: Identification



(A): Identical technologies
Choose curvature

(B): Identical curvature
Choose tech. diff.

(C): Technology differences
with PFPE

following cost function for industry g in country i:

$$c^V_{gi} = \left(\sum_f \alpha_{fg} \left(w_{fi}/\lambda^V_{fi} \right)^{1-\sigma} \right)^{1/(1-\sigma)} \tag{1}$$

where w_{fi} is the price of factor f in country i, λ^V_{fi} is a factor-augmenting technology parameter, and the non-negative α_{fg} parameters control factor intensities. Let $d_{fgi} = \partial c^V_{gi}/\partial w_{fi}$ be a unit input requirement. As is well known, the d_{fgi} satisfy

$$\frac{d_{Sgi}/d_{Sg\text{us}}}{d_{Ugi}/d_{Ug\text{us}}} = \left(\frac{w_{Si}/w_{S\text{us}}}{w_{Ui}/w_{U\text{us}}} \right)^{-\sigma} \left(\frac{\lambda^V_{Si}}{\lambda^V_{Ui}} \right)^{\sigma-1} \tag{2}$$

where $f = S,U$ indexes skilled and unskilled labour, $i =$ us indexes the United States, and we have normalized productivities using $\lambda^V_{f\text{us}} = 1$. This equation helps us explain the identification issue.

Suppose we only have cross-sectional data as, for example, in Trefler (1993) and Davis and Weinstein (2001). In particular, suppose that we only observe data on (d_{Ugi},d_{Sgi}) and (w_{Ui},w_{Si}) for two countries $i = 1,2$. Figure 2(A) plots an isoquant in (U,S) space. Points correspond to pairs (d_{Ugi}, d_{Sgi}) and slopes to $-w_{Ui}/w_{Si}$. Now consider the problem of disentangling whether cross-country variation in unit requirements is driven by substitution effects (mechanism *2a*) or factor-augmenting international technology differences (mechanism *2b*). One approach is to make the identifying assumption that technologies are internationally identical and then fit the data by choosing an isoquant curvature parameter σ to hit the two data points in panel (A). Another approach is to pin down σ using an external estimate and then to choose international technology differences $\lambda^V_{Si}/\lambda^V_{Ui}$ that generate the tangencies in panel (B). In between there are countless other approaches involving mixtures of curvature and international technology differences. Each approach can rationalize the data, that is, σ and $\lambda^V_{Si}/\lambda^V_{Ui}$ are not separately identified.

Trefler (1993) and Davis and Weinstein (2001) make claims about the importance of factor augmentation and/or substitution effects. How do they obtain identification? Trefler's identification assumption is productivity-adjusted factor price equalization (PFPE) i.e., $w_{fi}/\lambda^V_{fi} = w_{f\text{us}}$. Then the right side of equation (2) reduces to $\lambda^V_{Si}/\lambda^V_{Ui}$ and this is identified by the d_{fgi} data on the left side of (2). Identification is illustrated in panel (*C*) where the axes are productivity-adjusted factor inputs so that international differences in technology and factor prices disappear. Since all data for an industry are on a single point, Trefler cannot examine substitution effects along an isoquant (mechanism *2a*).

Davis and Weinstein's identification assumption is that there are only Hicks-neutral productivity differences so that $\lambda^V_{Si}/\lambda^V_{Ui} = 1$ i.e., mechanism (*2b*) disappears by assumption. Then the right side of equation (2) becomes $(w_{fi}/w_{f\text{us}})^{-\sigma}$, data on the d_{fgi} and w_{fi} identify σ, and they can analyze the role of the failure of factor price equalization.[7]

Summarizing, the presence of cross-country differences in relative prices *and* factor-augmenting technology creates an identification issue that has been ignored in the trade-and-endowments literature and whose resolution affects conclusions about the relative importance of mechanisms (*2a*) and (*2b*). In this paper, we use the technique illustrated in Figure 2(*B*). We appeal to Katz and Murphy (1992) and Acemoglu and Autor (2011) who use time series U.S. data to identify σ in the presence of linearly trending factor-augmenting (skill-biased) technical change. Acemoglu and Autor note that most researchers estimate σ to be between 1.4 and 2, and their own research puts σ between 1.6 to 1.8 (see pg. 1107-1109). We therefore use the midrange of 1.7. However, our results are not sensitive to using 1.4 or 2.[8]

3. A Quantitative Model

This section describes our quantitative general equilubrium model. We slightly extend the Caliendo and Parro (2015) model by adding skilled and unskilled labour. This framework will allow us to examine in general equilibrium the importance of the mechanisms described above in how countries absorb factor endowments. To get quickly to what is new we assume the reader is familiar with the Eaton and Kortum (2002) model and start with price determination as this will reduce notation.

3.1. Product Prices in Equilibrium

Let $i,j = 1,...,N$ index countries, $g,h = 1,...,G$ index goods or industries, and $\omega_g \in [0,1]$ index varieties of good g. A variety is potentially produced by many firms that sell into perfectly competitive international markets. Unit costs of producing ω_g in country i are given by $c_{gi}/z_{gi}(\omega_g)$ where $z_{gi}(\omega_g)$ is Fréchet-distributed efficiency, and c_{gi} is the component of unit cost that is

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[7] This discussion should not be viewed as a summary of Davis and Weinstein (2001). Among other things, they only analyze mechanism (*2a*), not (*2b*). Also note that they do not use data on w_{fi}, which raises an identification issue that pops up elsewhere in the literature. They implicitly solve the identification problem by proxying relative wages with relative endowments in their P4 and P5 specifications. In the spirit of Katz and Murphy (1992), this is related to a regression of log relative wages on log relative endowments and the coefficient is the inverse of σ. Romalis (2004) and Chor (2010) follow a similar strategy. Interestingly, we will provide some general equilibrium empirical support for this reduced-form approach in section 5.

[8] As shown in Table 2 below, we can also estimate sigma from the data by regressing productivity-adjusted relative wages on productivity-adjusted relative endowments in the tradition of Katz and Murphy (1992). This yields a sigma of 1.64. This is so close to 1.70 that our choice of which one to use makes no difference to our results.

common across varieties. c_{gi} is described in detail below. There are also iceberg trade costs: $\tau_{gi,j}$ is the cost of shipping any variety of g from country i to country j or, more succinctly, the cost of shipping (g,i) to j. We assume that the $\tau_{gi,j}$ satisfy the triangle inequality. As in Eaton and Kortum (2002) and Caliendo and Parro (2015), the price of ω_g in country j is therefore

$$p_{gj}(\omega_g) = \min_i \frac{c_{gi}\tau_{gi,j}}{z_{gi}(\omega_g)} \,. \tag{3}$$

3.2. *Households*

Household preferences in country i are given by:

$$U_i = \prod_{g=1}^{G} \left\{ \left(\int_0^1 x_{gi}(\omega_g)^{\frac{\rho_g - 1}{\rho_g}} d\omega_g \right)^{\frac{\rho_g}{\rho_g - 1}} \right\}^{\gamma_{gi}^U} \tag{4}$$

where $x_{gi}(\omega_g)$ is an amount of ω_g consumed in country i, $\rho_g > 1$ is the consumption elasticity of substitution within an industry, and the non-negative Cobb-Douglas share parameters satisfy $\sum_g \gamma_{gi}^U = 1$. Households have heterogeneous endowments of skilled and unskilled labour and hence heterogeneous incomes. A household's expenditures $\sum_g \left(\int p_{gi}(\omega_g) x_{gi}(\omega_g) d\omega_g \right)$ must not exceed its income.

3.3. *Goods Producers*

The technology for producing goods is exactly as in Caliendo and Parro (2015) but with multiple primary factors. Output $q_{gi}(\omega_g)$ of variety ω_g in country i is produced using:

1. A bundle of primary factors. For industry g in country i, the cost of the bundle is c_{gi}^V as in equation (1) .
2. Bundles of intermediate inputs $h = 1, \ldots, G$ where the hth bundle is CES with elasticity of substitution ρ_h. The cost of bundle h in country i is $P_{hi} \equiv \left[\int_0^1 \left[p_{hi}(\omega_h) \right]^{1-\rho_h} d\omega_h \right]^{1/(1-\rho_h)}$.

The upper-tier production function is Cobb-Douglas so that the resulting unit cost function for $q_{gi}(\omega_g)$ is $c_{gi}/z_{gi}(\omega_g)$ where $z_{gi}(\omega_g)$ is a variety-specific productivity drawn from a Fréchet distribution with location parameter 1 and shape parameter θ_g and

$$c_{gi} = \frac{\kappa_{gi}}{\lambda_{gi}^R} \left\{ \left[\sum_f \alpha_{fg} \left(w_{fi} / \lambda_{fi}^V \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \right\}^{\gamma_{gi}^V} \prod_{h=1}^{G} \left(P_{hi} \right)^{\gamma_{h,gi}^I} \,. \tag{5}$$

The term in braces is c_{gi}^V from equation (1). γ_{gi}^V is the share of primary inputs in costs and $\gamma_{h,gi}^I$ is the share of intermediate input bundle h in costs. V and I superscripts denote Value added and Intermediates, respectively. Cost shares vary by good g and location of production i so that all Cobb-Douglas parameters have (g,i) subscripts. We impose constant returns to scale: $\gamma_{gi}^V + \sum_{h=1}^{G} \gamma_{h,gi}^I = 1$.[9]

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[9] $\kappa_{gi} \equiv (\gamma_{gi}^V)^{-\gamma_{gi}^V} \prod_h (\gamma_{h,gi}^I)^{-\gamma_{h,gi}^I}$.

The remaining parameters capture productivity. As before, λ^V_{fi} is the efficiency of factor f in country i and captures factor-augmenting international technology differences. λ^R_{gi} is the efficiency of industry g in country i and captures Ricardian comparative advantage. Exploiting standard Fréchet properties:

$$P_{gi} = \kappa_g \left[\sum_{j=1}^{N} \left(c_{gj}\tau_{gj,i}\right)^{-\theta_g} \right]^{-1/\theta g} , \tag{6}$$

where $\kappa_g \equiv \Gamma((1+\theta_g-\rho_g)/\theta_g)^{1/(1-\rho_g)}$ and $\theta_g > \rho_g - 1$. Let $\pi_{gi,j}$ be the share of g that j sources from i. Again, exploiting standard Fréchet properties,

$$\pi_{gi,j} = \frac{\left(c_{gi}\tau_{gi,j}\right)^{-\theta_g}}{\sum_{i'=1}^{N}\left(c_{gi'}\tau_{gi',j}\right)^{-\theta_g}} . \tag{7}$$

The richness of the model means there are a lot of parameters. Table 1 reviews them.

3.4. *Equilibrium*

We make one small depature from Caliendo and Parro. They assume that only intermediate input bundles can be traded. We assume that final goods can be traded as well since such trade is a prominent feature of our data. This is a trivial extension that does not affect any of the derivations above. It does, however, slightly alter the equilibrium conditions. Let Q_{gi} be the value of (g,i) output summed across varieties.

Let D_j be country j's trade deficit. We follow Caliendo and Parro in treating the D_j as exogenous. Globally, trade is balanced so that $\sum_j D_j = 0$.

This allows us to write down an expression for country j's expenditures on good g produced by country i:

$$E_{gi,j} \equiv \pi_{gi,j} \sum_{h=1}^{G} \gamma^I_{g,hj} Q_{hj} \;+\; \pi_{gi,j}\gamma^U_{gj} \left(\sum_{h=1}^{G} \gamma^V_{hj} Q_{hj} \;+\; D_j \right) . \tag{8}$$

This data identify is notationally demanding and an understanding of it is not necessary for the reader to work through the rest of the model. Therefore, a detailed explanation of it is relegated to Appendix A.[10] We can now state the key equilibrium conditions.

Income equals expenditure: Setting sales of (g,i) equal to expenditures on (g,i) yields

$$Q_{gi} = \sum_{j=1}^{N} E_{gi,j} . \tag{9}$$

Goods market clearing by variety: Setting supply equal to demand for a variety of (g,i) yields

$$q_{gi}(\omega_g) = \sum_{j \in J(i)} \tau_{gi,j} \frac{p_{gj}(\omega_g)^{-\rho_g}}{P_{gj}^{1-\rho_g}} E_{gi,j} \tag{10}$$

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[10] For a reader who needs at least a rough understanding of equation (8) we note the following. The first term is expenditures by producers in country j on intermediate input g sourced from country i. The second term is expenditures by consumers in country j on final good g sourced from country i. The term in parentheses is country j's spending power, which is the sum of income earned by j's primary factors $\gamma^V_{hj}Q_{hj}$ is value added generated in (h,j) and a transfer D_j from the rest of the world.

Table 1: Notation

Indexes	
g, h	goods (usually g uses h as an input)
i,j	countries (usually i exports to j)
f	factors ($f = S$,U for skilled and unskilled labour)
Share Parameters	
γ^V_{gi}	Value added as a share of total costs for g produced in i
$\gamma^I_{h,gi}$	Intermediate input h as a share of total costs for g produced in i
γ^U_{gi}	consumption of good g as a share of country i's total consumption (U for Utility) Note: $\gamma^V_{gi} + \sum_h \gamma^I_{h,gi} = 1$ and $\sum_g \gamma^U_{gi} = 1$
α_{fg}	factor intensity parameter for factor f used to produce good g
κ_g, κ_{gi}	Functions of γ^V_{gi}, γ^I_{gi}, θ_g and ρ_g. See section 3.3
Key Technology Parameters	
λ^R_{gi}	Ricardian productivity when producing good g in country i
λ^V_{fi}	factor-augmenting productivity of factor f in country i (V for value added)
Elasticities	
σ	elasticity of substitution between skilled and unskilled labour
θ_g	Fréchet shape parameter for good g
ρ_g	elasticity of substitution between varieties of good g
Flows from country i to country j	
$\tau_{gi,j}$	iceberg cost of shipping good g from country i to country j
$\pi_{gi,j}$	share of g that country j sources from country i, $\sum_i \pi_{gi,j} = 1$
$M_{gi,j}$	country j's imports of good g from country i
X_{gi}	country i's total exports of good g
Good g produced in Country i	
c_{gi}	common input cost of producing one unit of good g in country i
c^V_{gi}	value added in one unit of good g produced in country i
d_{fgi}, $\widetilde{d}_{fgi}$	factor f needed to produce one dollar of good g in country i. ($\widetilde{d}_{fgi}$ when measured in productivity-adjusted units)
$b_{gi,hj}$	value of intermediate input g from country i needed to produce one dollar of h in j
Factors	
V_{fi}, $\widetilde{V}_{fi}$	country i's endowment of factor f. ($\widetilde{V}_{fi}$ when measured in productivity-adjusted units)
w_{fi}, $\widetilde{w}_{fi}$	wages of factor f in country i. ($\widetilde{w}_{fi}$ when measured in productivity-adjusted units)

where $J(i)$ is the set of importers that source ω_g from country i.[11]

Factor market clearing: Each country i is endowed with an inelastic supply of primary factors V_{fi}. Factor demand at the industry level per dollar of sales is given by

$$d_{fgi} = \left(\gamma^V_{gi}/\lambda^V_{fi}\right) \left[\alpha_{fg} \left(w_{fi}/\lambda^V_{fi}\right)^{-\sigma}\right] \Big/ \left[\textstyle\sum_{f'} \alpha_{f'g} \left(w_{f'i}/\lambda^V_{f'i}\right)^{1-\sigma}\right] . \tag{11}$$

The proof appears in Appendix B. Factor demands are usually defined per unit of output and this is how we defined d_{fgi} earlier. We now define it per dollar of output in order to seamlessly match the WIOD data.[12] Hence $d_{fgi}Q_{gi}$ is the amount of factor f employed producing $(g{,}i)$ and factor market clearing is

$$\textstyle\sum_{g=1}^{G} d_{fgi}Q_{gi} = V_{fi} \,. \tag{12}$$

Equilibrium: Equilibrium is a set of prices w_{fi} and $p_{gi}(\omega_g)$ which clear factor markets domestically (equation 12) and clear product markets internationally (equation 10) subject to producers minimizing costs and consumers maximizing utility. In equations (10) and (12), the variables $(P_{gi}{,}c_{gi}{,}\pi_{gi,j}{,}E_{gi,j}{,}Q_{gi})$ satisfy equations (5)–(9).

4. Data and Calibration

Unless otherwise noted, all data come from the World Input-Output Database (WIOD) as assembled by Timmer et al. (2015). The database has the advantage of providing information on the full world input-output matrix and satisfying all world input-output identities. Our data cover 39 developed and developing countries and 23 industries in the year 2006.[13] WIOD includes data on output, consumption, trade, and purchases of intermediate inputs. It also includes labour by educational attainment: Skilled workers possess some tertiary education while unskilled workers are the remainder of the labour force. For each type of labour, WIOD reports hours worked and compensation by industry and country. We measure wages as compensation divided by hours and employment as hours worked. The direct input requirement d_{fgi} is hours worked divided by sales.

The parameters to be calibrated are listed in table 1. The Cobb-Douglas share parameters γ^U_{gi}, γ^V_{gi} and $\gamma^I_{h,gi}$ are taken from the WIOD share data. As emphasized by de Gortari (2019), these fit the consumption and production share data perfectly. α_{Sg} and $\alpha_{Ug} = 1 - \alpha_{Sg}$ are pinned down by equation (11) for the United States.[14] We do not let the θ_g vary by industry as this would introduce yet another source of comparative advantage into our model (Fieler, 2011, Caron et al., 2014). We drop the g subscript on θ_g and set θ=5.03, which is its meta study median value across

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[11] $\tau_{gi,j}$ appears just after the summation in order to convert demand for delivered goods (q/τ) into demand for supplied goods (q).

[12] This redefinition does not affect anything we wrote above because we have only worked with ratios d_{Sgi}/d_{Ugi} and in ratios the scaling of d_{fgi} (per unit or per dollar) cancels out.

[13] The 2013 vintage of WIOD covers 35 sectors. We aggregate up to 23 industries to make results comparable to Davis and Weinstein (2001) and Trefler (1993, 1995). No industries are dropped. See Appendix C for details. We use 2006 because it is the most recent year before the Great Recession and the subsequent trade collapse and also because it is the year used by Burstein and Vogel (2017).

[14] $\alpha_{fg} = w^{\sigma}_{f\text{us}} V_{fg\text{us}} / (\sum_{f'} w^{\sigma}_{f'\text{us}} V_{f'g\text{us}})$.

32 papers that estimate θ using tariff and/or freight rate data (Head and Mayer, 2014, table 5). As discussed at the end of section 2, we choose $\sigma = 1.70$.[15]

There are two features of our model that provide natural starting points for estimating the remaining parameters of the model. The first is substitution between skilled and unskilled labour (controlled by σ) which appears in equation (11). We use (11) as the basis for estimating the λ^V_{fi}. The second is productivity heterogeneity (controlled by θ) and this appears in the gravity equation (7) which we use to estimate the $\tau_{gi,j}$ and λ^R_{gi}.

4.1. The Gravity Equation and Calibration of the $\tau_{gi,j}$ and λ^R_{gi}

We build on Waugh (2010) and Levchenko and Zhang (2012). From equation (7),

$$\ln \pi_{gi,j}/\pi_{gj,j} = -\theta \ln(c_{gi}) + \theta \ln(c_{gj}) - \theta \ln(\tau_{gi,j}) \tag{13}$$

where we set $\tau_{gj,j} = 1$. We parameterize $\theta \ln(\tau_{gi,j})$ as $\psi_g x_{ij}$ where ψ_g is a vector of regression coefficients and x_{ij} is a vector of standard covariates. We then estimate the gravity equation

$$\ln \pi_{gi,j}/\pi_{gj,j} = \delta_{gi} - \delta_{gj} - \psi_g x_{ij} + \varepsilon_{gi,j} \tag{14}$$

where the δ_{gi} are exporter-industry fixed effects. (When $i = j$ the 'exporter' is the domestic producer.) $\varepsilon_{gi,j}$ captures unmeasured trade costs and model misspecification. Estimating this equation separately for each industry g generates estimates of $\theta \ln \tau_{gi,j} = \hat{\psi}_g x_{ij}$ and hence of the $\tau_{gi,j}$.[16]

Levchenko and Zhang (2012) use the estimated δ_{gi} to recover the $c_{gi}/c_{g,\text{us}}$ and show that when the γ^V_{gi} and $\gamma^I_{h,gi}$ are independent of i, the $c_{gi}/c_{g,\text{us}}$ can be used to recover the Ricardian productivity parameters $\lambda^R_{gi}/\lambda^R_{g,\text{us}}$. In Appendix D.1 we extend their method to the case where the γ^V_{gi} and $\gamma^I_{h,gi}$ depend on i. Online appendix table B1 displays a transformation of our measures of $\lambda^R_{gi}/\lambda^R_{g,US}$ that also includes aggregate productivity.

4.2. The Factor Demand Equation and Calibration of the λ^V_{fi}

Manipulating equation (11) to obtain equation (2) and introducing an error to allow for functional-form misspecification, we obtain

$$d_{gi} = \beta_i + \nu_{gi} \quad \text{where} \quad d_{gi} \equiv \frac{d_{Sgi}/d_{Sg,\text{us}}}{d_{Ugi}/d_{Ug,\text{us}}} \quad \text{and} \quad \beta_i \equiv \left(\frac{w_{Si}/w_{S\text{us}}}{w_{Ui}/w_{U\text{us}}}\right)^{-\sigma} \left(\frac{\lambda^V_{Si}}{\lambda^V_{Ui}}\right)^{\sigma-1}. \tag{15}$$

We estimate $d_{gi} = \beta_i + \nu_{gi}$ by regressing d_{gi} on country dummies. The estimated dummies are estimates of the β_i. The regression pools across industries and countries and uses weighted least squares with weights ω^L_{gi} that are industry g's share of country i's total employment ($\sum_g \omega^L_{gi} = 1$).

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[15] As is well known the ρ_g play almost no role in Eaton-Kortum style models, including ours. We thus follow Levchenko and Zhang (2012) in setting them to a common value of 4. This satisfies the requirement $\theta > \rho - 1$.

[16] x_{ij} consists of the following bilateral dummy variables: common border; common language; colonial relationship; common customs union; preferential trade area; and, following Eaton and Kortum (2002), dummies for each of the distance intervals [0, 350], (350, 750], (750, 1,500], (1,500, 3,000], (3,000, 6,000], and >6,000 miles. The coding of the customs union and preferential trade dummies is described in Appendix C. All other data are from CEPII. See `http://www.cepii.fr/cepii/en/bdd_modele/presentation.asp?id=8` by Thierry Mayer.

This places greater weight on industries that are more important for the country and less weight on small industries. The resulting estimate of each β_i is just the weighted average $\widehat{\beta}_i = \sum_{g=1}^{23} \omega_{gi}^{L} d_{gi}$. We calibrate factor-augmenting productivities using

$$\frac{\lambda_{Si}^{V}}{\lambda_{Ui}^{V}} \quad = \quad \left(\frac{w_{Si}/w_{S\text{us}}}{w_{Ui}/w_{U\text{us}}}\right)^{\frac{\sigma}{(\sigma-1)}} \widehat{\beta}_i^{\frac{1}{(\sigma-1)}} \quad = \quad \left(\frac{w_{Si}/w_{S\text{us}}}{w_{Ui}/w_{U\text{us}}}\right)^{\frac{\sigma}{(\sigma-1)}} \left(\sum\nolimits_g \omega_{gi}^{L} \frac{d_{Sgi}/d_{Sg,\text{us}}}{d_{Ugi}/d_{Ug,\text{us}}}\right)^{\frac{1}{(\sigma-1)}} \quad . \tag{16}$$

Finally, absolute advantage depends on the product of the λ_{fi}^{V} and λ_{gi}^{R} (see equation 5) so we cannot separately determine the level of each. We must normalize one or the other. Given our focus on endowments we load absolute advantage on the λ_{fi}^{V} and pin down their levels by normalizing the λ_{gi}^{R}. The normalization is described at the end of Appendix D.1. We will flag the rare instances of results that are not invariant to the choice of normalization.

4.3. *Are the λ_{fi}^{V} Reasonable?: Evidence from Development Accounting*

Caselli and Coleman (2006) have a different way of computing factor-augmenting technology differences. Consider a single-good economy with an aggregate production function

$$Y_i = \left[\alpha_U (\lambda_{Ui}^{cc} V_{Ui})^{\frac{\sigma-1}{\sigma}} + \alpha_S (\lambda_{Si}^{cc} V_{Si})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{17}$$

where Y_i is both output and income and the cc superscript indicates that these are Caselli and Coleman productivities. Equating the marginal product of factor f with its factor price yields $w_{fi} = \alpha_f (\lambda_{fi}^{cc})^{\frac{\sigma-1}{\sigma}} (Y_i/V_{fi})^{\frac{1}{\sigma}}$ or $\lambda_{fi}^{cc} = w_{fi}^{\frac{\sigma}{\sigma-1}} \alpha_f^{-\frac{\sigma}{\sigma-1}} (V_{fi}/Y_i)^{\frac{1}{\sigma-1}}$. Hence,

$$\frac{\lambda_{Si}^{cc}}{\lambda_{Ui}^{cc}} = \left(\frac{\alpha_U}{\alpha_S}\right)^{\frac{\sigma}{\sigma-1}} \left(\frac{w_{Si}}{w_{Ui}}\right)^{\frac{\sigma}{\sigma-1}} \left(\frac{V_{Si}}{V_{Ui}}\right)^{\frac{1}{\sigma-1}} \quad . \tag{18}$$

This is identical to the λ_{fi}^{cc} in Caselli and Coleman (2006) for the case without capital. See their footnote 7. Figure 3 plots our $\lambda_{Si}^{V}/\lambda_{Ui}^{V}$ against $\lambda_{Si}^{cc}/\lambda_{Ui}^{cc}$ replicating the left panel of figure 1. The fit is very good (slope=0.996 and $R^2 = 0.95$), which provides external validation of our calibrated factor-augmenting productivities.[17]

The figure leads to two additional conclusions. First, it establishes a strong link between the HOV and development accounting literatures. Second, it is surprising that the multi-sector HOV model reproduces results from a single-sector aggregate production function. This is likely driven by a strong cross-country correlation between V_{Si}/V_{Ui} and the average of the d_{Sgi}/d_{Ugi}. This would happen, for instance, if within a country all 23 of the d_{Sgi}/d_{Ugi} co-moved due to a common factor. w_{Si}/w_{Ui} is an obvious candidate for such a common factor. This is a first indication that cross-country variation in relative endowments is driven more by substitution effects (mechanism *1b*) than output allocation effects (mechanism *1a*). We return to this similarity between single-sector and multi-sector models in section 5.

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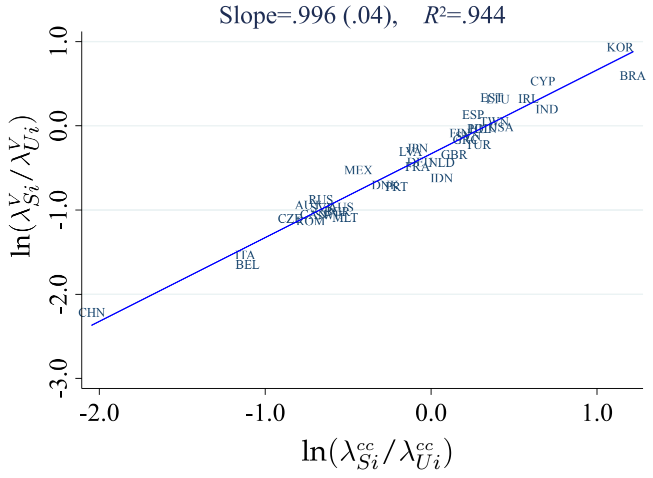
[17] Turning to λ_{Ui}^{V} and λ_{Si}^{V} separately, Caselli and Coleman (2006, figures 1 and 2) show that while their λ_{Si}^{cc} have the expected positive correlation with real income per worker, their λ_{Ui}^{cc} do not. In contrast, the correlation between λ_{fi}^{V} and gdp per capita in logs is 0.72 for skilled labour and 0.85 for unskilled labour. Thus, our method improves on Caselli and Coleman in this dimension.

Figure 3: Our Method vs. Development Accounting



Notes: The horizontal axis is the Caselli-Coleman relative productivities from equation (18). The vertical axis is our relative productivities from equation (16). The OLS line is also plotted.

We have explored the fit of the model relative to external estimates for one moment, the Caselli-Coleman productivities. With all of our primitive parameters in hand, we can generate all equilibrium endogenous variables from our quantitative model. Appendix D.2 discusses the solution algorithm. Appendix figure A1, explores the fit for the two targeted moments (the $\pi_{gi,j}$ and d_{fgi}) as well as six key untargeted moments.

5. How Do Economies Adjust to Endowments? Evidence from Actual Data

We argued in the introduction that many questions in the literature on endowments, trade and wages depend on the components of two decompositions:

1. Differences in how countries absorb their endowments of skilled and unskilled labour can be decomposed into (*a*) between-industry differences in output mix and (*b*) within-industry differences in skill intensities.

2. Within each industry, cross-country differences in skill intensities can be decomposed into contributions from cross-country differences in (*a*) relative wages and (*b*) skill-biased factor-augmenting technology.

For example, the traditional factor price equalization version of Heckscher Ohlin and Vanek (e.g., Bowen, Leamer and Sveikauskas, 1987) assumes that all of the adjustment is through output mix. Helpman (1984) and Davis and Weinstein (2001) introduce a role for relative wages while Trefler (1993) introduces a role for factor-augmenting technology with PFPE. Although we take skill-biased technology into account, we will treat it as exogenous and will abstract from its endogenous determination in which it might both affect and be affected by trade as in Gancia and Bonfiglioli (2008) and Gancia and Zilibotti (2009).

Before examining our two decompositions using the quantitative model, in this section we turn to the actual data for evidence. We start with our second decomposition. From equation (2),

$$\ln \frac{d_{Sgi}/d_{Sg\text{us}}}{d_{Ugi}/d_{Ug\text{us}}} = -\sigma \ln \left(\frac{w_{Si}/w_{S\text{us}}}{w_{Ui}/w_{U\text{us}}} \right) + (\sigma - 1) \ln \left(\frac{\lambda^V_{Si}}{\lambda^V_{Ui}} \right) + \nu_{gi}. \tag{19}$$

where $\sigma = 1.7$ and ν_{gi} is an error that accounts for functional form misspecification. We can therefore decompose the variance of the left-side skill intensities into the variances of the wage and technology terms, a covariance term because the two, and the residual variance. Together, the first three three terms explain 51.7% of the variance in log skill intensities: the variance of log relative wages explains 38.6%, skill-biased technology 25.3%, and the covariance between the two is negative and explains -12.1%. The remaining 48.3% is explained by idiosyncratic factors ν_{gi} that vary by industry and country.[18] However, this decomposition is partial equilibrium in that it does not account for the fact that skill-biased technology induces changes in relative wages.[19] Indeed, this is one reason why wages and technology are correlated. In section 7 we will therefore turn to the quantitative model to endogenize wages.

We next turn to what the actual data tell us about our first decomposition, namely, the decomposition of variation in relative endowments $\ln V_{Si}/V_{Ui}$ into output mix and skill intensities. It will be useful to refine this decomposition of relative endowments into output mix (1*a*), wages (2*a*) and technology (2*b*).

The left panel of figure 4 plots actual data for $\ln(w_{Si}/w_{Ui})$ against $\ln(V_{Si}/V_{Ui})$. The negative fit means that relative factor prices are quite responsive to relative endowments. Factor price equalization does not hold. Nor does the weaker factor price insensitivity theorem of Leamer and Levinsohn (1995). The question is then how much of the residual variation is due to output mix or technology.

To do this, we introduce factor-augmenting technology by measuring wages and endowments in productivity-adjusted terms. As Leontief (1953) observed long ago, U.S. labour is much more productive than Indian labour so it is not clear what the sum of U.S. and Indian labour means economically. The solution is to measure endowments in efficiency units before summing them. To this end, define

$$\widetilde{V}_{fi} = \lambda^V_{fi} V_{fi}\ , \qquad \widetilde{w}_{fi} = w_{fi}/\lambda^V_{fi}\ , \qquad \widetilde{d}_{fgi} = \lambda^V_{fi} d_{fgi}\ , \qquad \widetilde{V}_{fw} = \textstyle\sum_i \widetilde{V}_{fi} \tag{20}$$

as productivity-adjusted endowments, wages, factor input usage, and world endowments, respectively.

The right panel of figure 4 shows that the negative wage-endowment correlation also holds when wages and endowments are measured in productivity-adjusted terms. Remarkably, the fit is essentially perfect. This begs the question of how to interpret the correlation within the context of our model.

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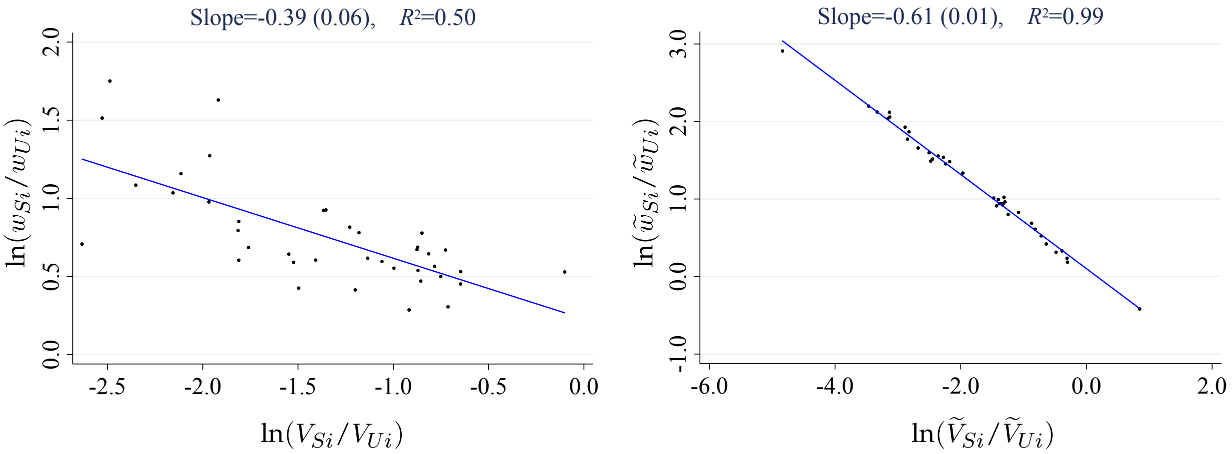
[18] These cannot be Ricardian factors. The d_{Sgi} and d_{Ugi} are both proportional to λ^R_{gi} so that d_{Sgi}/d_{Ugi} is independent of λ^R_{gi}.

[19] For example, if wages were exactly determined by productivity differences, we would expect to see 150% of the variance in skill intensities attributed to wage differences, 25% to productivity differences, and -124% to their covariance based on a variance decomposition with σ=1.7 and an R^2 of 0.517.

Figure 4: Wages Respond to Domestic Endowments



Notes: Each point is a country. The OLS lines of best fit are plotted along with their slopes (standard errors) and R^2s.

Consider the factor market clearing equation (12), $\sum_g d_{fgi}Q_{gi} = V_{fi}$. Recall that the only place the d_{fgi} and V_{fi} appear in the model is in this equation. Multiplying through by λ^V_{fi} yields $\sum_g \widetilde{d}_{fgi}Q_{gi} = \widetilde{V}_{fi}$. Dividing this productivity-adjusted market-clearing condition for S by the market-clearing condition for U yields

$$\ln\left(\widetilde{w}_{Si}/\widetilde{w}_{Ui}\right) = \ln CA_i - \sigma^{-1}\ln\left(\widetilde{V}_{Si}/\widetilde{V}_{Ui}\right) \ , \tag{21}$$

where

$$CA_i \equiv \frac{\sum_g \alpha_{Sg}\left[c^V_{gi}(w_{Si},w_{Ui})\right]^{\sigma-1} Q^{\sigma}_{gi}}{\sum_g \alpha_{Ug}\left[c^V_{gi}(w_{Si},w_{Ui})\right]^{\sigma-1} Q^{\sigma}_{gi}} \ .$$

See Appendix E for a proof of equation (21). CA_i captures all the multiple and potentially offsetting sources of comparative advantage in the model that affect industrial structure $\{Q_{gi}\}_g$. The right panel of figure 4 shows that equation (21) fits well in terms of the $R^2 = 0.99$. It also fits well in terms of the slope provided that CA_i is not too correlated with $\ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})$. If this is the case, the slope should be $-1/\sigma$ which, given our figure 4 slope of –0.61 implies a σ of 1.64. This is in the tight 1.6–1.8 range favoured by Acemoglu and Autor (2011, p. 1107–1109) and very close to the value of 1.7 we used to estimate λ^V_{fi}. We conclude from this discussion that in productivity-adjusted units, relative wages are pinned down by relative endowments. The production structure of the economy $\{Q_{gi}\}_g$ plays at best a small role. Indeed, relative wages are determined as if by a single-sector model. This feature is surprising for a trade model and suggests that *the wage and technology mechanisms are much more important than the output-mix mechanism*.

To be clear the right panel of figure 4 in no way implies that $\ln CA_i$ is zero; rather it implies that its variation across countries is small relative to the variation in endowments. As we shall see in section 6, the Heckscher-Ohlin-based link between output mix and endowments found by Baldwin (1971), Romalis (2004), Chor (2010), and Morrow (2010) is also be present in our data.

Table 2: Mechanism (*b*) in the Cross-Section

	Figure 4, Left Panel			Figure 4, Right Panel		
	$\ln \frac{w_{Si}}{w_{Ui}} = \beta_0 + \beta_1 \ln \frac{V_{Si}}{V_{Ui}}$			$\ln \frac{\widetilde{w}_{Si}}{\widetilde{w}_{Ui}} = CA_i - \sigma^{-1} \ln \frac{\widetilde{V}_{Si}}{\widetilde{V}_{Ui}}$		
Data Type	R^2	β_1	$-\beta_1^{-1}$	R^2	β_1	σ
1. Actual Data	0.50	–0.39	2.56	0.99	–0.61	1.64
2. Model-Generated Data	0.48	–0.31	3.22	0.99	–0.59	1.70
3. Model Generated, $\tau_{gi,j} = 1$	0.44	–0.34	2.94	0.95	–0.61	1.64

Notes: The table reports the results of the regressions listed in the top row. The right panel is equation (21) where the theory states that $-\beta_1^{-1} = \sigma$.

Figure 4 has three other interesting implications. *First*, it tightly links our work to the single-sector results that underlie much of the development accounting literature e.g., Caselli (2005), Caselli and Coleman (2006), Caselli and Feyrer (2007) and Caselli (2016). *Second*, figure 4 provides a empirical justification for proxying relative wages by endowments as in Davis and Weinstein (2001), Chor (2010), and Romalis (2004). It also explains what their approach ignores: the term CA_i. *Third*, the slope in the left panel of figure 4 is flatter than in the right panel, which means the left panel has a larger implied σ (2.56 versus 1.64). This goes to the heart of our figure 2 discussion of identification. To fit choice of techniques d_{Sgi}/d_{Ugi} without appealing to the λ_{fi}^V, one needs greater curvature in isoquants i.e., a larger σ.

All of the results so far in this section are correlations in the actual data. They are not causal relationships. It is therefore of interest to examine whether the correlations can be replicated by the causal mechanisms in the model. Table 2 reports the figure 4 correlations using actual data (row 1), model-generated data (row 2), and model-generated data from a model with no trade costs (row 3). The two blocks correspond to the left and right panels of figure 4. The model-based correlations in rows 2 and 3 do indeed replicate the correlations in the actual data. The second block of results are estimates of equation (21). The slope β_1 is the inverse of σ and the implied σ is very close to our assumed value of 1.70. Thus, our model can generate the correlations in figure 4. This lends support for our claim that wage and technology mechanisms are much more important than the output-mix mechanism.

The table makes two other lesser points. First, row 3 shows that trade costs do not explain why wages are determined almost exclusively by domestic endowments with little reference to the international environment. Second, the $-\beta_1^{-1}$ and σ columns illustrate our points about identification of substitution effects versus factor augmenting technology differences. When the latter are ignored, the substitution effect needed to fit the data becomes larger, much larger than most estimates in the literature.

5.1. A Note on Directed Technical Change

In this paper we treat the $\lambda^V_{Si}/\lambda^V_{fU}$ as exogenous productivity parameters. In this section, we briefly and informally relax this assumption by relating our approach to the the large literature on directed technical change (Acemoglu, 1998, 2009). This literature, summarized in Acemoglu (2009, chapter 15), explains how $\lambda^V_{Si}/\lambda^V_{fU}$ may respond to endowments V_{Si}/V_{Ui}. There are two offsetting effects of endowments on technology. On the one hand, innovation is directed towards the expensive factor (the price effect). On the other hand, innovation is directed towards the more abundant factor (the market-size effect). If $\sigma > 1$, the market-size effect dominates so that technical change is directed towards a country's abundant factor. See Acemoglu (1998, 2009) and, in an international context, Acemoglu and Zilibotti (2001), Gancia and Bonfiglioli (2008), Gancia and Zilibotti (2009) and Blum (2010).[20]

While it is beyond the scope of this paper to model directed technical change, we can take a reduced-form approach by appealing to the model in (Acemoglu, 2009, chapter 15). Consider a closed economy which behaves as if aggregate production is as in equation (17).[21] Firms decide whether to innovate towards increasing the productivity of S or U depending on aggregate relative endowments of the two factors as well as, critically, on the elasticity of substitution σ. Acemoglu (2009, eq. 15.27) derives the following equation, which contains most of the economics of directed technical change:

$$\ln \frac{\lambda^V_{Si}}{\lambda^V_{Ui}} = \beta_0 + (\sigma - 1)\ln\left(\frac{V_{Si}}{V_{Ui}}\right) \tag{22}$$

where β_0 is an exogenous parameter of Acemoglu's model and σ is the (derived) elasticity of substitution.

To investigate, we estimate equation (22) using our 39 countries/observations and estimates of $\lambda^V_{Si}/\lambda^V_{Ui}$. The R^2 is 0.29 and the coefficient on log relative endowments is 0.58 with a robust standard error of 0.18 and a wild clustered bootstrap p-value of 0.006. The estimated coefficient implies $\sigma - 1 = 0.58$ or $\sigma = 1.58$, which is extremely close to the Acemoglu and Autor (2011) midpoint estimate of 1.70 that we use. We conclude from this that the actual data display a correlation between endowments and technology which is in the same direction as that

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[20] The directed technical change mechanism is different from the Burstein and Vogel mechanism: In the former it is a choice while in the latter it is not a choice but a technological feature of size. Given the complexity of the underlying trade model, the Burstein and Vogel is an impressive modelling simplification.

[21] Acemoglu has two sectors and sector f produces output using machines and factor f. Firms in sector f choose how much to innovate and innovation raises the productivity of factor f i.e., raises λ^V_{fi}. The output of the two sectors are aggregated using a CES production function. This aggregate production function implies a derived elasticity of substitution between capital and labour σ which is the inverse of the elasticity of relative wages with respect to endowments i.e., Acemoglu's derived elasticity σ is the same as our elasticity σ. For more details see the discussion following Acemoglu's equation 15.19.

emphasized in the directed technical change literature.[22]

6. How do Economies Adjust to Endowments?: Model-Based Evidence

The previous section used a partial equilibrium approach to informally examine features of the actual data. In this section we examine our first model-based decomposition of endowments into output mix and skill intensity. In the next section we examine our second model-based decomposition of skill intensity into wages and technology.

There are a number of possible thought experiments. We could change the endowment of each country one at a time and report the decomposition. We might also consider how our results depend on the size and direction of the endowment change. This would lead to a very large number of results. Instead, we consider a thought experiment which is tightly aligned with endowments-based theories of comparative advantage. Specifically, by a judicious reallocation of endowments worldwide, we eliminate endowments as a source of comparative advantage and ask how the resulting change in endowments affects each countries' output mix and skill intensities.

We implement this as follows. Endowments-based comparative advantage is switched off when the $c^V_{gi}/c^V_{g'i}$ are the same for all countries. It is easy to see from equation (1) that a sufficient condition for this is that $\widetilde{w}_{Si}/\widetilde{w}_{Ui}$ is the same for all countries.[23] We know from figure 4 and row 2 of table 2 that this condition will be true when the $\widetilde{V}_{Si}/\widetilde{V}_{Ui}$ are the same across countries. We therefore switch off endowments-based comparative advantage by choosing the $\widetilde{V}'_{fi}$ so that

$$\frac{\widetilde{V}'_{Si}}{\widetilde{V}'_{Ui}} = \frac{\widetilde{V}_{Sw}}{\widetilde{V}_{Uw}}$$

where $\widetilde{V}_{fw} = \sum_i \widetilde{V}_{fi}$ so that all countries have the same relative endowments. Restated, we are putting each country onto the diagonal of an Edgeworth-Bowley box in productivity-adjusted endowment space.[24] To pin down the level of endowments we follow Costinot et al. (2012) in targeting income shares: We scale the $\widetilde{V}'_{fi}$ by a country-specific constant chosen so that equilibrium

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[22] We have wondered whether there is something in the construction of the λ^V_{fi} that makes equations (21)–(22) fit so well and return estimates of σ that are so close to 1.70. We have not found any theoretical explanation. In this context note that equation (22) has an R^2 that is 'only' 0.29 so this equation is not an identity. Also note that the one restriction we can find that would lead to the equation (21) regression fitting the data perfectly is the restriction that $\alpha_g \equiv \alpha_{Sg}/\alpha_{Ug}$ is the same for all industries g. In this case CA_i is independent of i and becomes a true intercept. But in this case all industries share a common factor intensity and there is no endowments-based comparative advantage. Not only is this case factually false (α_g varies a lot across industries and, correspondingly, the elements of CA_i are far from unity – the intercept in the right panel of figure 4 is 0.10 with a robust bootstrapped standard error of 0.019), but it is also inconsistent with our finding of endowments-based comparative advantage in Section 6.1. Finally, our $\lambda^V_{Si}/\lambda^V_{Ui}$ are very similar to those calculated using the Caselli-Coleman approach which uses a very different formula.

[23] From equation (1), $(c^V_{gi})^{1-\sigma} = \widetilde{w}_{Ui}[\alpha_{Ug} + \alpha_{Sg}(\widetilde{w}_{Si}/\widetilde{w}_{Ui})^{1-\sigma}]$. Hence $c^V_{gi}/c^V_{g'i}$ is the same for all i and each industry pair (g,g') if $\widetilde{w}_{Si}/\widetilde{w}_{Ui}$ is the same for all i. Implicit in any discussion of endowments-based comparative advantage is the assumption that the α_{Sg}/α_{Ug} vary across industries. In this case, $c^V_{gi}/c^V_{g'i}$ is the same for all i and each industry pair (g,g') if and only if $\widetilde{w}_{Si}/\widetilde{w}_{Ui}$ is the same for all i.

[24] This choice of the $\widetilde{V}'_{fi}$ reduces the cross-country variance of $\ln(\widetilde{w}'_{Si}/\widetilde{w}'_{Ui})$ almost to zero in our model, which in turn reduces the cross-country variance of $\ln(c^{V'}_{gi}/c^{V'}_{g,\text{us}})$ almost to zero for each g. The variances are all less than 0.01.

income shares are the same as in the benchmark equilibrium. This ensures that we are switching off comparative advantage without changing absolute advantage.[25]

Consider how an economy changes as we move from an equilibrium with no endowments-based comparative advantage (variables denoted with primes) to the benchmark equilibrium. In what follows we only use model-generated data. For any variable x let $\Delta x = \ln x - \ln x' = \ln(x/x')$. We begin by observing that the regression of $\Delta \ln \widetilde{w}_{Si}/\widetilde{w}_{Ui}$ on $\Delta \ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})$ has a slope of –0.61 (0.02) and an R^2 of 0.95 i.e., the relationship in changes matches the relationship in levels reported in row 2 of table 2. This is yet more evidence that the wage substitution mechanism (1*b*) is present and more important than the industry reallocation mechanism (1*a*).

The factor-market clearing condition is $\widetilde{V}_{fi} = \sum_g \widetilde{d}_{fgi} Q_{gi}$. We can thus decompose the change in endowments into within-industry changes in $\widetilde{d}_{fi}$ and between-industry changes in Q_{gi}. Totally differentiating $\widetilde{V}_{fi} = \sum_g \widetilde{d}_{fgi} Q_{gi}$ and differencing across skilled and unskilled labour yields:

$$\underbrace{\sum_{g=1}^{G} (\theta_{Sgi} - \theta_{Ugi}) \Delta \ln Q_{gi}}_{B_i} + \underbrace{\sum_{g=1}^{G} \left(\theta_{Sgi} \Delta \ln \widetilde{d}_{Sgi} - \theta_{Ugi} \Delta \ln \widetilde{d}_{Ugi} \right)}_{W_i} = \Delta \ln \widetilde{V}_{Si}/\widetilde{V}_{Ui} \tag{23}$$

where

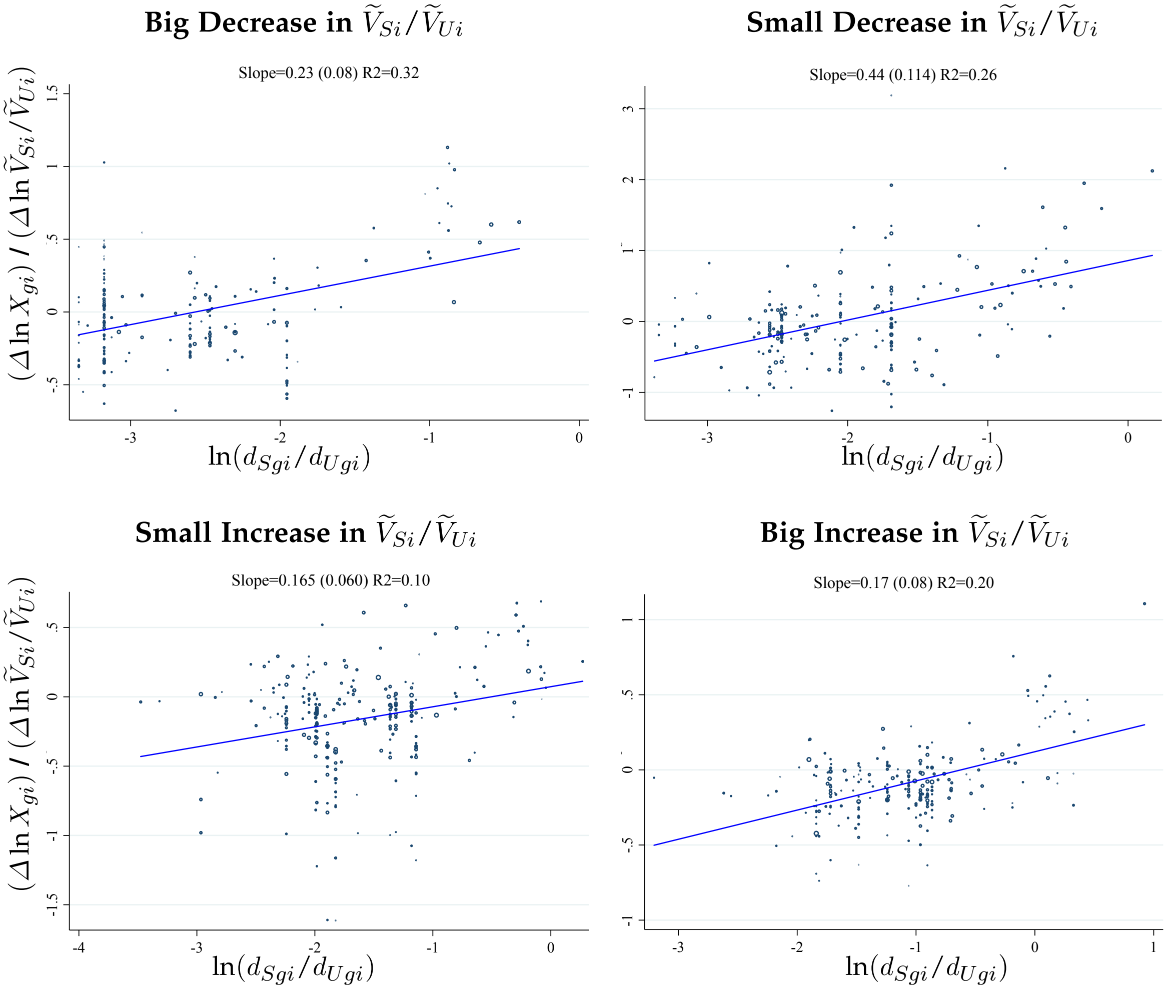
$$\theta_{fgi} = \left(\frac{\widetilde{d}_{fgi} Q_{gi}}{\widetilde{V}_{fi}} + \frac{\widetilde{d}'_{fgi} Q'_{gi}}{\widetilde{V}'_{fi}} \right) /2 \,.$$

The θ_{fgi} are factor shares ($\sum_g \theta_{fgi} = 1$) averaged across the two equilibria. The proof is in Appendix E. The B_i term is the *B*etween-industry reallocation effect and corresponds to the output-mix mechanism. The W_i term is the wage effect that leads to *W*ithin-industry substitution towards the cheaper factor. It corresponds to skill-intensity mechanism.

Table 3 reports B_i as a percentage of $\Delta \ln \widetilde{V}_{Si}/\widetilde{V}_{Ui}$. While it varies across countries, on average it accounts for only 4.1% of the absorption of endowments. Thus, our model-based decomposition shows that the skill-intensity mechanism is much more important than the output-mix mechanism.[26]

As noted in more detail in the introduction, our decomposition result is consistent with some of the econometric results in the migration literature (Card and Lewis, 2007, Lewis, 2004, Gandal et al., 2004), the trade literature (as surveyed by Goldberg and Pavcnik, 2007), as well as the quantitative results in Parro (2013).[27]

Figure 5: A Counterfactual Assessment of The Heckscher-Ohlin Trade Prediction



Notes: Each marker is an industry in a country. Marker size is proportional to export shares $X_{gi}/\sum_{g'} X_{g'i}$ so that each country's largest trade flows appear more prominently. The OLS line of best fit is also displayed. The slope, standard errors and R^2 are based on weighted least squares regressions with weights equal to the square root of export shares and standard errors two-way clustered by industry and country.

Table 3: Decomposition of Endowment Differences: Industry Reallocation Share

Cyprus	12.0%	Austria	5.7%	Ireland	3.3%	Italy	1.8%
Turkey	11.6%	Taiwan	5.5%	Romania	3.2%	Spain	1.6%
Indonesia	9.7%	Greece	5.5%	Czech	3.0%	Australia	1.6%
Belgium	8.3%	Estonia	5.2%	China	2.8%	UK	0.8%
Sweden	8.3%	Latvia	4.3%	Korea	2.8%	Denmark	0.7%
Slovenia	7.1%	Canada	4.1%	Finland	2.8%	USA	0.5%
Bulgaria	6.7%	Hungary	4.1%	Poland	2.5%	Germany	0.4%
India	6.2%	Portugal	3.9%	Brazil	2.5%	Mexico	0.1%
Slovakia	6.0%	Lithuania	3.7%	France	2.0%	Japan	0.0%
Malta	5.7%	Netherl.	3.6%	Russia	1.9%	Mean	4.1%

Notes: The table reports the percentage of the endowment change that is accounted for by between-industry change i.e., by industrial reallocation or mechanism (1*a*). 100 minus this number is the percentage of the endowment change accounted for by within-industry change i.e., wage changes that lead to substitution towards the cheaper factor or mechanism (1*b*). Mathematically, the table reports the first term in equation (23) as a percentage of the counterfactual change in relative endowments i.e., 100 $B_i/\Delta\ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})$. All data are model-generated.

6.1. The Heckscher-Ohlin Trade Prediction

The finding that industrial reallocation (mechanism 1*a*) is small means that trade movements are not that important for thinking about how an economy absorbs its endowments. Yet the model's trade prediction is correct. In the 2 × 2 Heckscher-Ohlin model skill-abundant countries export skill-intensive goods. While this is not a theoretically derivable implication of our model, we can ask whether it holds quantitatively as we switch off endowments-based comparative advantage. As before, all countries start with the same ratio of productivity-adjusted endowments $\widetilde{V}'_{Si}/\widetilde{V}'_{Ui}$ which is then changed to its actual value $\widetilde{V}_{Si}/\widetilde{V}_{Ui}$. Let X_{gi} be country i's gross exports of g and define $\Delta\ln X_{gi} \equiv \ln X_{gi} - \ln X'_{gi}$. Figure 5 plots model-generated $\Delta\ln X_{gi}/\Delta\ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})$ against skill intensity d_{Sgi}/d_{Ugi}. Each point is an industry-country pair. We expect a positive relationship: As a country becomes more skill abundant, it increases its exports of skill-intensive goods and reduces its exports of unskilled-intensive goods. Note that $\Delta\ln X_{gi}$ and $\Delta\ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})$ have the same sign for skill-intensive industries and opposite signs for unskilled-intensive industries so data should lie either in the top right or bottom left, generating an upward sloping relationship.

To allow for non-linearities in how our model responds to changes in endowments, we break our 39 countries into four approximately equal-sized groups based on whether the countries are becoming more skill-abundant or less and on whether the change is large or small. The positive

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[25] Costinot et al. (2012) choose $\lambda^{R'}_{gi}$ so that the $\lambda^{R'}_{gi}/\lambda^{R'}_{g'i}$ are the same across countries. This eliminates Ricardian-based comparative advantage. The levels of the $\lambda^{R'}_{gi}$ are then shifted by a country-specific term $\lambda^{R'}_{i}$ to hold incomes constant, which eliminates changes in absolute advantage. Writing $\widetilde{V}'_{fi}$ as $\lambda^{V'}_{fi}V_{fi}$, we are following Costinot et al., but with the $\lambda^{V'}_{fi}$ in place of the $\lambda^{R'}_{gi}$.

[26] It should be clear that identical results hold in non-productivity-adjusted terms.

[27] It is less consistent with Hanson and Slaughter (2002) and Burstein et al. (2020). Again, this may be due to the fact that in our cross-country setting relative to their within-US cross-state and cross-commuting-zone, there is likely less scope for migration and weaker forces for factor price equalization.

relationship is evident in each panel. Similar results hold when we pool countries with large and small changes. Further, when we replace ΔX_{gi} with ΔQ_{gi} we get almost identical results. We conclude that there is a 2×2 Heckscher-Ohlin trade result in operation in the model. Further, relative endowments have an effect on the structure of trade and production.

An alternative is to run a regression motivated by Romalis (2004) using actual data. Specifically, modify equation (14) by introducing a Romalis-inspired interaction between factor intensities ($d_{Sg,\text{us}}/d_{Ug,\text{us}}$) and factor abundance($V_{Si}/V_{Ui}$)

$$\pi_{gi,j} = \beta \ln \frac{d_{Sg,\text{us}}}{d_{Ug,\text{us}}} \cdot \ln \frac{V_{Si}}{V_{Ui}} + \delta_{gj} + \delta_{ij} + \varepsilon_{gi,j} \ .$$

where we expect $\beta > 0$ because country i is a low-cost producer of g if i is skill-abundant and g is skill-intensive. In this regression, we control for destination-good gj and origin-destination ij fixed effects. In our data we estimate $\beta = 0.85$ with standard errors 0.16 where clustering is three way by gi, gj and ij. One- and two-way clustered standard errors are very similar.[28] We again conclude that there is a Heckscher-Ohlin trade result in operation. We also conclude that our finding of a Heckscher-Ohlin effect does not conflict with our statement that it is not a dominant mechanism by which endowments are absorbed.

7. A Model-Based Decomposition of Skill Intensities into Wages and Technology

We next return to how differences in skill intensities d_{Sgi}/d_{Ugi} are driven by differences in wages w_{Si}/w_{Ui} and skill-biased factor-augmenting technology $\lambda^V_{Si}/\lambda^V_{Ui}$. Our previous thought experiment of reallocating endowments internationally will not help us here because it does not allow the $\lambda^V_{Si}/\lambda^V_{Ui}$ to change.[29] Instead, we switch off the $\lambda^V_{Si}/\lambda^V_{Ui}$ as a source of comparative advantage by setting them to unity. This induces equilibrium changes in skill intensities and relative wages. The interpretation of the decomposition is then as follows. Eliminating the $\lambda^V_{Si}/\lambda^V_{Ui}$ as a source of comparative advantage has direct and indirect effects on skill intensities. The direct effects are partial equilibrium and hold wages constant. The indirect effects are due to general equilibrium wage changes induced by the technology changes.

Documenting these direct and indirect effects is a new contribution to the literature on international differences in skill intensities e.g., Keesing (1971), Dollar, Wolff and Baumol (1988), Wood (1994), Davis and Weinstein (2001) and Lewandowski, Park, Hardy and Du (2019). In these papers, which largely predate the Eaton-Kortum model, there is no general equilibrium model to help disentangle direct and indirect effects. The direct effects that we measure are similar to what was examined in the pre-Eaton-Kortum HOV literature where the skill-intensity implications of different specifications of technology were examined without modeling general equilibrium wage changes. To cite just a few of many examples, Trefler (1993, 1995) compares the HOV model with and without factor-augmenting international technology differences and Davis and Weinstein (2001) compare the HOV model with and without Hicks neutral international

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[28] Experiments with bootstrapping suggest standard errors that are also very tight.

[29] Since the λ^V_{fi} do not change because they are exogenous parameters, any change in d_{fgi} due to a V_{fi}-induced change in w_{fi} will, by construction, attribute 100% of the change in techniques to wages.

technology differences.[30] We revisit the literature by examining indirect general equilibrium effects.

This section is organized as follows. We first describe our thought experiment of switching off comparative advantage by eliminating variation in λ^V_{fi}. This is analogous to how Costinot et al. (2012) switched off comparative advantage by switching off the Ricardian λ^R_{gi}. We then benchmark the impacts of switching off the λ^V_{fi} by comparing their impacts to those from eliminating variation in λ^R_{gi}. In so doing, we show that both are similarly important. Finally, after switching off λ^V_{fi}, we decompose the resulting changes in input requirements into direct technology effects and indirect general equilibrium wage effects.

7.1. *Switching Off Technology as a Source of Comparative Advantage*

We switch off technology using the approach of Costinot et al. (2012).

1. **Switching Off Factor-Augmenting Productivity:** We switch off factor-augmenting productivity as a source of comparative advantage by setting the $\lambda^V_{fi} = 1$ for all fi. As noted by Costinot et al. this will also affect absolute advantage and we neutralize this by changing each country's aggregate productivity so that the country's new share of world income is the same as its baseline share.[31]

To benchmark the importance of factor-augmenting international productivity, we compare its effect with that of Ricardian international productivity differences. We know that the latter are very important (Costinot et al., 2012), but we have not yet established that the λ^V_{fi} parameters are important. This leads us to our second exercise:

2. **Switching Off Ricardian Comparative Advantage:** As in Costinot et al. (2012), we switch off Ricardian comparative advantage by setting the $\lambda^R_{gi}/\lambda^R_{g'i}$ equal across countries. In particular, we replace each λ^R_{gi} with a $\lambda^{R'}_{gi}$ that satisfies

$$\frac{\lambda^{R'}_{gi}}{\lambda^{R'}_{g'i}} = \frac{\lambda^R_{g,\text{us}}}{\lambda^R_{g',\text{us}}} \quad \forall g, g', i \; .$$

   Again, we change each country's aggregate productivity so that its new share of world income is the same as its baseline share.

It should be easy to see from equation (11) that Ricardian productivity has no direct effect on *per dollar* input requirements. In order to place factor-augmenting and Ricardian productivity differences on equal footing, we shift from input requirements *per dollar of output* ($\widetilde{d}_{fgi}$) to input requirements *per unit of output*. The latter is just

$$\overline{d}_{fgi} \equiv \widetilde{d}_{fgi} \cdot c_{gi} \; .$$

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[30] See their specifications P3 and T3.

[31] While shares do not change, expenditure levels do change. A country's expenditure is its share of world expenditures s_i times world expenditures E_w (which equals world income). A country's expenditure $s_i E_w$ thus has two components, one which we do not allow to change (s_i) and one which changes by the same amount for all countries (E_w).

Table 4: Total (Direct plus General Equilibrium) Effects

	Switch off λ^V_{fi}	Switch off λ^R_{gi}
Inputs per unit of output		
1. $\overline{d}_{Sgi}/\overline{d}_{Ugi}$	0.43	0.05
2. $\overline{d}_{Sgi}$	0.20	0.32
3. $\overline{d}_{Ugi}$	0.05	0.31
Wages		
4. w_{Si}/w_{Ui}	0.07	0.02
5. w_{Si}	0.03	0.01
6. w_{Ui}	0.01	0.00
Productivity-adjusted wages		
7. $\widetilde{w}_{Si}/\widetilde{w}_{Ui}$	0.15	0.02
8. $\widetilde{w}_{Si}$	0.06	0.12
9. $\widetilde{w}_{Ui}$	0.02	0.10

Notes: Each entry is the variance of the log change in the indicated outcome as we move from the baseline equilibrium to the equilibrium in which either λ^V_{fi} is switched off (first column) or λ^R_{gi} is switched off (second column). As an example, consider the unit input requirements for skilled labour in row 2. Let $\overline{d}_{Sgi}$ be its baseline value and $\overline{d}'_{Sgi}$ be its value when λ^V_{fi} is switched off. Then 0.20 is the variance of $\ln(\overline{d}_{Sgi}/\overline{d}'_{Sgi})$ calculated across industries g and countries i. Likewise, 0.32 is the corresponding variance when λ^R_{gi} is switched off.

This is necessary because, for reasons specific to CES, $\widetilde{d}_{fgi}$ depends directly only on λ^V_{fi} and not on λ^R_{gi}. In contrast, $\overline{d}_{fgi}$ depends directly on both.

7.2. *The Importance of* λ^V_{fi} *Relative to* λ^R_{gi}

We first compare the impacts of switching off the productivity parameters in table 4. Let $\overline{d}_{fgi}$ be a unit input requirement in the baseline equilibrium i.e., with both λ^V_{fi} and λ^R_{gi} switched on. Let $\overline{d}'_{fgi}$ be an input requirement when λ^V_{fi} is switched off in a new equilibrium. Then a measure of the general equilibrium impact of switching off λ^V_{fi} is the log change $\ln(\overline{d}'_{fgi}/\overline{d}_{fgi})$. In table 4 we report the variance of these log changes calculated across industries and countries. Results separately by country are similar. The first column of the table is the variance of the log change for the case where λ^V_{fi} is switched off. The second column is for the case where λ^R_{gi} is switched off. We can repeat this exercise for any endogenous variable and in the table we do so for nine of the most relevant variables for our decomposition.

We see that λ^V_{fi} is more important than λ^R_{gi} whenever we are dealing with a ratio of skilled to unskilled labour (rows 1, 4 and 7). This should not be surprising given that Ricardian productivity differences do not directly affect relative quantities. See footnote 18 above. In contrast, λ^R_{gi} is more important than λ^V_{fi} whenever we are dealing with skilled labour (row 2) and unskilled labour (row 3) although effects for skilled labor are comparable. In short, λ^V_{fi} is roughly as important as the heavily studied λ^R_{gi} in these dimensions.

7.3. *Decomposition into Direct and General Equilibrium Effects*

We now decompose changes in $\overline{d}_{fgi}$ into direct and general equilibrium effects to examine the distinct impacts of wages and technology on input requirements. To do this, we start by decomposing the total log change in $\overline{d}'_{fgi}/\overline{d}_{fgi}$ as follows:

$$\ln\left(\frac{\overline{d}'_{fgi}}{\overline{d}_{fgi}}\right) = \ln\left(\frac{\overline{d}^{D}_{fgi}}{\overline{d}_{fgi}}\right) + \ln\left(\frac{\overline{d}^{P}_{fgi}}{\overline{d}^{D}_{fgi}}\right) + \ln\left(\frac{\overline{d}'_{fgi}}{\overline{d}^{P}_{fgi}}\right) \tag{24}$$

where we now describe $\overline{d}^{D}_{fgi}$ and $\overline{d}^{P}_{fgi}$. Recall that $\overline{d}_{fgi}$ depends on wages and price indexes (P_{gi}) and that wages and price indexes vary endogenously as we switch off the productivity parameters. $\overline{d}^{D}_{fgi}$ is $\overline{d}_{fgi}$ evaluated at the new productivity parameters, but the initial wages and prices. Likewise, $\overline{d}^{P}_{fgi}$ is $\overline{d}_{fgi}$ evaluated at the new productivity parameters and price indexes, but at initial wages. Appendix F provides mathematical expressions for $\overline{d}^{D}_{fgi}$ and $\overline{d}^{P}_{fgi}$. Therefore, the first term on the right side of the above equation is the log change in unit requirements holding wages and price indexes at their initial levels. The second term is the additional log change due to changes in the price index, holding wages at their initial levels. It is one way of isolating the role of input-output linkages emphasized by Caliendo and Parro (2015). The third term is the additional log change due to changes in wages.

Taking the variance of both sides of the above equation yields

$$\mathcal{T} = \mathcal{D} + \mathcal{P} + \mathcal{W} + \mathcal{C}$$

where $\mathcal{T}$, $\mathcal{D}$, $\mathcal{P}$ and $\mathcal{W}$ are the variances of the four terms in equation (24) and $\mathcal{C}$ collects the covariance terms. It is convenient to divide through by the total variance in order to express elements of the decomposition as shares:

$$1 = \frac{D}{\mathcal{T}} + \frac{P}{\mathcal{T}} + \frac{W}{\mathcal{T}} + \frac{C}{\mathcal{T}}. \tag{25}$$

Table 5 reports the elements of this equation multiplied by 100. The $\mathcal{D}/\mathcal{T}$, $\mathcal{P}/\mathcal{T}$, and $\mathcal{W}/\mathcal{T}$ columns must be non-negative and the four columns must sum to 100%. Consider the first row of table 5, which deals with the variance of log changes in $\ln(\overline{d}_{Sgi}/\overline{d}_{Ugi})$. Again, the variance is pooled across industries and countries. The first column shows that 289% of this variance is due to the direct partial equilibrium effect holding wages and price indexes constant. The second column shows that 0% of the variance is due to general equilibrium changes in price indexes. This is because P_{gi} does not show up in the expression for *relative* input requirements. The third column shows that 49% of the variance is due to general equilibrium changes in wages. The fourth column shows that -238% of the variance is due to general equilibrium effects underlying the covariance term. The shares of 289% and -238% are at first glance surprising, but have a simple interpretation. The direct effect induces a change in unit input requirements, say an increase in unit requirements of skilled labour. This raises skilled wages which in turn reduces skill intensities. This latter negative correlation between skilled wages and skilled requirements shows up in the negative covariance term -238%. Further, since the covariance term is negative, the remaining terms must sum to more than 100% and this shows up in the 289% direct effect.

Table 5: Total (Direct plus General Equilibrium) Effects

	Panel A: Switch off λ^{V}_{fi}				Panel B: Switch off λ^{R}_{gi}			
	$\mathcal{D}/\mathcal{T}$	$\mathcal{P}/\mathcal{T}$	$\mathcal{W}/\mathcal{T}$	$\mathcal{C}/\mathcal{T}$	$\mathcal{D}/\mathcal{T}$	$\mathcal{P}/\mathcal{T}$	$\mathcal{W}/\mathcal{T}$	$\mathcal{C}/\mathcal{T}$
Inputs per unit of output								
1. $\overline{d}_{Sgi}/\overline{d}_{Ugi}$	289	0	49	-238	0	0	100	0
2. $\overline{d}_{Sgi}$	283	0*	50	-233	79	20	19	-18
3. $\overline{d}_{Ugi}$	294	1	48	-243	81	21	23	-25
Wages								
4. w_{Si}/w_{Ui}	0	0	100	0	0	0	100	0
5. w_{Si}	0	0	100	0	0	0	100	0
6. w_{Ui}	0	0	100	0	0	0	100	0
Productivity-adjusted wages								
7. $\widetilde{w}_{Si}/\widetilde{w}_{Ui}$	289	0	49	-238	0	0	100	0
8. $\widetilde{w}_{Si}$	290	0	50	-240	0	0	100	0
9. $\widetilde{w}_{Ui}$	291	0	50	-242	0	0	100	0

Notes: Each row is a different endogenous equilibrium outcome. We switch off either λ^{V}_{fi} or λ^{R}_{gi} and calculate the total variance of the log change in the row's outcome. The total variance appeared above in table 4. In this table we decompose the total variance into a direct effect $\mathcal{D}/\mathcal{T}$, a price-index effect $\mathcal{P}/\mathcal{T}$, a wage effect $\mathcal{W}/\mathcal{T}$ and a covariance term $\mathcal{C}/\mathcal{T}$. See equation (25). These effects are multiplied by 100 to express them as percentages of the total variance. Within each panel, the first three columns must be non-negative and the sum across the four columns must be 100. One can prove theoretically that 0 entries must be zero. The sole exception is indicated by a *, where the zero is due to rounding.

For Ricardian productivity (Panel B), the results are similarly intuitive. Ricardian productivity differences have no direct effect on relative techniques nor any effect through prices (row 1) as top and bottom 'cancel out' for relative techniques. However, Ricardian differences do affect unit inputs (rows 2 and 3). The last three columns then show the endogenous effects of price indexes and wages. For unit input requirements, the direct effects are understandably larger, with smaller general equilibrium and covariance effects.

The first three rows of table 5 contain the main point of the table. They show that switching off the productivity parameters, especially the λ^V_{fi}, induces large general equilibrium feedback effects on unit input requirements. As a result, the older literature on the role of international technology differences for international differences in unit input requirements missed very important general equilibrium wage and price effects.

The remaining rows of table 5 report results for wages and productivity-adjusted wages. The results are intuitive. In rows (4)-(6) of Panel A, it is trivial that 100% of the variance in wages is accounted for by general equilibrium wage adjustment. In rows (7)-(9), changes in factor augmenting productivity, have a large direct effect on productivity-adjusted wages, but the endogenous response of observed wages induces a strong adjustment in the opposite direction.

There are three takeaways from this section. First, factor-augmenting productivity λ^V_{fi} is comparable in importance to Ricardian productivity λ^R_{gi} for thinking about unit input requirements, wages, and productivity-adjusted wages. See table 4. Second, while the pre-Eaton-Kortum factor endowments literature largely explored the direct relationship between productivity and unit input requirements, it did not have the modelling tools to fully examine the general equilibrium aspects of this relationship. We show that these aspects are of first-order importance (table 5). Third, when we used the actual data to decompose skill intensities into wages and technology in section 5, we did not have tools for deciding whether to attribute the correlation of wages and technology to wages or to technology. Table 5 shows that much of the correlation should be attributed to technology rather than wages. Summarizing, tables 4 and 5 show that factor-augmenting technology is important and explains a substantial portion of the international variation in skill intensities, both directly as well as indirectly through general equilibrium impacts on wages.

8. Theoretical Predictions for Trade in Factor Services

In this section, we examine whether using actual data that incorporates both factor-augmenting and Ricardian productivity differences resolves "missing trade." We find that it does not and, using our model, offer evidence that trade costs are the primary determinant of missing trade and not differences in preferences. We start by defining familiar expressions for the factor content of trade before moving to our empirical analysis.

8.1. The World Input-Output Accounts

Let **B** be the world input-output matrix. The fundamental input-output equation states that gross output ($\mathbf{Q}_i$) is used for intermediate inputs ($\mathbf{B}\mathbf{Q}_i$), final consumption ($\mathbf{C}_i$) and trade ($\mathbf{T}_i$). That is,

$\mathbf{Q}_i = \mathbf{B}\mathbf{Q}_i + \mathbf{C}_i + \mathbf{T}_i$ or

$$\mathbf{T}_i = (\mathbf{I} - \mathbf{B})\mathbf{Q}_i - \mathbf{C}_i \tag{26}$$

where $\mathbf{I}$ is an identity matrix. More specifically, $\mathbf{B}$ is a $GN \times GN$ matrix whose (gi,hj) element $b_{gi,hj}$ is the value of intermediate inputs (g,i) needed per dollar of (h,j) output. $\mathbf{Q}_i$ is a GN column vector whose gi element is Q_{gi} and whose gj element for $j \neq i$ is zero. $\mathbf{C}_i$ is a GN column vector whose gj element $C_{gj,i}$ is the value of country i's consumption of good g produced in country j. $\mathbf{T}_i$ is a GN column vector whose gi element X_{gi} is the value of country i's exports of g and whose gj element for $j \neq i$ is $-M_{gj,i}$, the negative of country i's imports of g from j.[32] Equation (26) is the goods market clearing condition and always holds in both the data and the quantitative model. Appendix D.3 sets up these vectors and matrices in more detail and equates their elements back to primitives of the model so that it is clear how they are simulated in our quantitative model.

8.2. The Vanek Factor Content of Trade Prediction

Following Trefler and Zhu (2010), we define the Vanek-consistent factor content of trade as the factors employed *worldwide* to produce country i's trade flows $\mathbf{T}_i$. Letting $\mathbf{D}_f$ be a $1 \times GN$ matrix with typical element d_{fgi} and defining $\mathbf{A}_f \equiv \mathbf{D}_f(\mathbf{I} - \mathbf{B})^{-1}$, the Vanek-consistent factor content of trade is

$$F_{fi} \equiv \mathbf{A}_f \mathbf{T}_i \, . \tag{27}$$

It is 'Vanek-consistent' because, as the next theorem shows, under certain conditions F_{fi} equals its Vanek prediction $V_{fi} - s_i \sum_j V_{fj}$ where s_i is country i's share of world consumption ($\sum_i s_i = 1$).

Theorem 1 *(Trefler and Zhu, 2010):*

$$F_{fi} = \left(V_{fi} - s_i \textstyle\sum_{j=1}^{N} V_{fj} \right) + \mathbf{A}_f \left(\mathbf{C}_i - s_i \mathbf{C}_w \right) \, . \tag{28}$$

The proof appears in Appendix G. $\mathbf{C}_i = s_i \mathbf{C}_w$ is a sufficient condition for the Vanek equation to hold. To better understand the condition, note that $\mathbf{C}_j = s_j \mathbf{C}_w$ in non-matrix notation is $C_{gi,j} = s_j C_{gi,w}$ for all g and i, meaning that country j's consumption is proportional to world consumption and the proportion s_j is the same for all goods g from all locations i. If there are no intermediate inputs then all inputs are for consumption ($M_{gi,j} = C_{gi,j}$) and all production is consumed somewhere in the world ($Q_{gi} = C_{gi,w}$) so that $C_{gi,j} = s_j C_{gi,w}$ is just the gravity equation (without distance) $M_{gi,j} = s_j Q_{gi}$.

Theorem 1 answers the confusing question about whether the Vanek equation is an accounting identity or a testable prediction. In the following corollary, we show that when preferences are identical internationally and when there are no trade costs in our model, then $\mathbf{C}_i = s_i \mathbf{C}_w$ i.e., the Vanek prediction holds with identity.

Corollary 1 *Suppose that preferences are identical internationally (γ_{gi}^{U} is independent of i for all g) and that there are no trade costs ($\tau_{gi,j} = 1$ for all g, i and j). Then $\mathbf{C}_i = s_i \mathbf{C}_w$ and*

$$F_{fi} = V_{fi} - s_i \textstyle\sum_{j=1}^{N} V_{fj} \, .$$

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[32] The subscripts are dense, but keeping track of them is unimportant for what follows.

The proof appears in Appendix G.

While the Vanek equation is an identity in the data when preferences are internationally identical and there are no trade costs, it is nevertheless of empirical interest for three reasons. First, in the real world that generated the WIOD data, there are large trade costs so the Vanek equation does not hold as an accounting identity. The Vanek equation can thus be tested using WIOD data. Note that this is equivalent to testing $\mathbf{C}_i = s_i\mathbf{C}_w$. Also note that if $\mathbf{C}_i \neq s_i\mathbf{C}_w$, then the error term is $\mathbf{A}_f\left(\mathbf{C}_i - s_i\mathbf{C}_w\right)$, which does depend on technology via $\mathbf{A}_f$. Second, corollary 1 leaves open the question of whether the failure of the Vanek equation is due to trade costs or international preference differences. We use our quantitative model to show that the failure is almost entirely the result of trade costs. Third, it is an open question whether the Vanek equation would come close to holding if trade costs were partially but not fully eliminated.[33]

8.3. The Empirics of Trade in Factor Services

We now turn to empirics. We start by replicating past results for trade in factor services in this section. Trade in factor services is given by Corollary 1. Consider the left panels of figure 6 which plot the factor content of trade F_{fi} (vertical axis) against its Vanek predictor $V_{fi} - s_iV_{fw}$ (horizontal axis). Both F_{fi} and $V_{fi} - s_iV_{fw}$ are scaled by V_{fi}. The top left panel is for unskilled labour, each point is a country, and we are plotting actual data (not model-generated data). The panel displays a strong positive relationship between endowments and factor contents and, correspondingly, the OLS line of best fit has a remarkably high R^2 of 0.90. In contrast, the best-fit line has a slope that is much below unity (slope = 0.17, s.e. = 0.01), which means that there is much less trade in factor services than predicted by the theory. Missing trade is in evidence. Similar conclusions emerge for skilled labour, which is plotted in the middle-left panel.

Pushing into territory that has never been explored, recall that the spirit of Heckscher-Ohlin is about the impact of *relative* factor abundance i.e. of abundance of skilled labour *relative* to unskilled labour. This has never been examined in a Vanek context. In the bottom-left panel we plot $(F_{Si}/V_{Si}) - (F_{Ui}/V_{Ui})$ against $(V_{Si} - s_iV_{Sw})/V_{Si} - (V_{Ui} - s_iV_{Uw})/V_{Ui}$. There is clearly a strong positive relationship between relative endowments and the relative factor content of trade. The R^2 of 0.90 is high, but again missing trade is evidenced by the slope of 0.18.

Before turning to missing trade, there are a number of points that need to be addressed. We display the scaled plots because the unscaled plots are visually dominated by the two largest countries, China and the United States. That said, the unscaled results lead to exactly the same conclusions: The R^2s for unskilled labour, skilled labour and skilled less unskilled labour are 0.93, 0.98, and 0.92, respectively, and the slopes are 0.17 (0.01), 0.13 (0.003), and 0.17 (0.01).

As before, we measure endowments in efficiency units before summing them to the world level: $\widetilde{V}_{fw} = \sum_i \widetilde{V}_{fi}$. Recall that the only place the d_{fgi} and V_{fi} appear in the model is in the factor-

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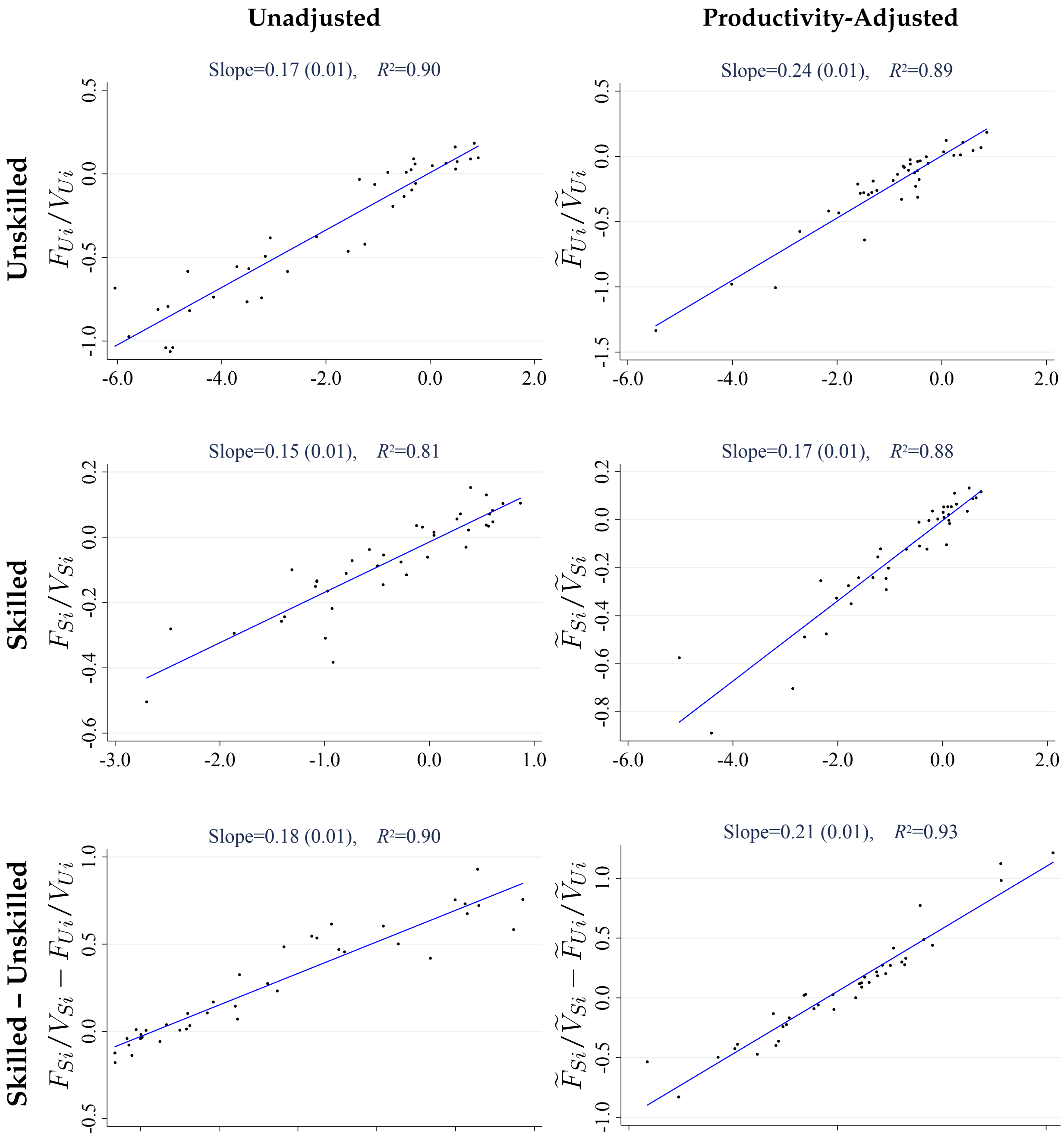
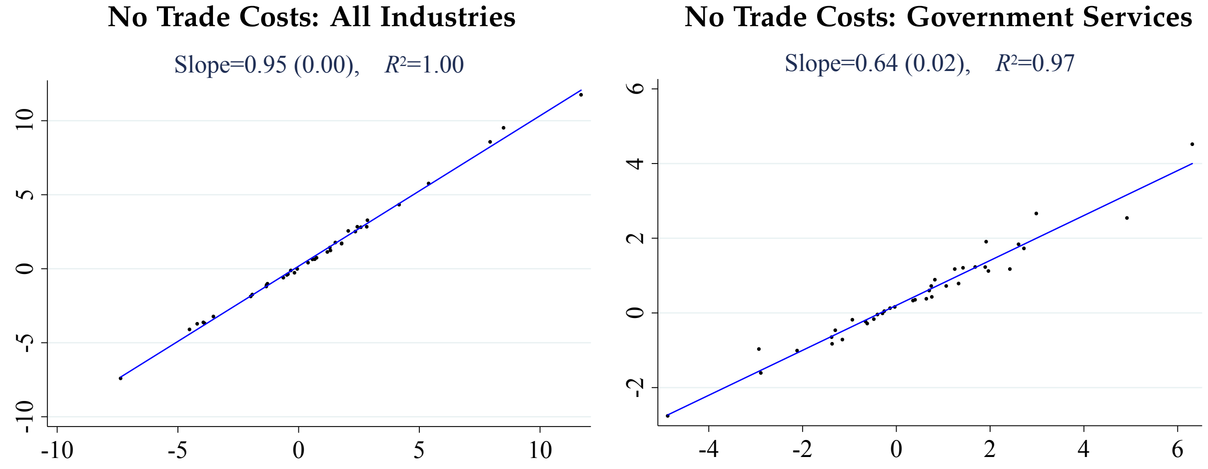
[33] The ideas in this subsection were anticipated by Deardorff (1982), Helpman and Krugman (1985), Trefler (1996), Feenstra (2004), Trefler and Zhu (2010), and Burstein and Vogel (2011). See especially Feenstra's (2004, p. 56) comment that imposing gravity without distance on the data (which is close to imposing $\mathbf{C}_i = s_i\mathbf{C}_w$) comes close to a hypothesis about an identity. Staiger et al. (1987) anticipated our quantitative strategy using the Michigan Model; however, they arrived at the surprising and opposite conclusion that tariff reductions worsen the fit of the Vanek equation.

Figure 6: The Vanek Equation



Notes: The top left panel plots F_{Ui}/V_{Ui} on the vertical axis against $(V_{Ui} - s_i V_{Uw})/V_{Ui}$ on the horizontal axis. Each point is a country. Actual data (rather than model-generated data) are plotted. The top right panel plots the same, but in productivity-adjusted units: $\widetilde{F}_{Ui}/\widetilde{V}_{Ui}$ against $(\widetilde{V}_{Ui} - s_i \widetilde{V}_{Uw})/\widetilde{V}_{Ui}$. The middle two panels repeat this for skilled labour. The bottom left panel plots the difference between skilled and unskilled labour, $[(F_{Si}/V_{Si}) - (F_{Ui}/V_{Ui})]$ against $[(V_{Si} - s_i V_{Sw})/V_{Si}] - [(V_{Ui} - s_i V_{Uw})/V_{Ui}]$. The bottom right panel plots the same, but in productivity-adjusted units. The OLS line of best fit is displayed along with its slope (standard error) and R^2.

Figure 7: Vanek Equation: Role of Trade Costs and Preferences


No Trade Costs: All Industries

No Trade Costs: Government Services

Notes: The panels plots $\widetilde{F}_{Si}/\widetilde{V}_{Si} - \widetilde{F}_{Ui}/\widetilde{V}_{Ui}$ on the vertical axis against $(\widetilde{V}_{Si} - s_i\widetilde{V}_{Sw})/\widetilde{V}_{Si} - \widetilde{F}_{Ui}(\widetilde{V}_{Ui} - s_i\widetilde{V}_{Uw})/\widetilde{V}_{Ui}$. In the left panel, the points are model-generated data from an equilibrium in which trade costs have been eliminated in every sector ($\tau_{gi,j} = 1$). In the right panel, the points are model-generated data from an equilibrium in which trade costs have been eliminated only in the Government Services sector. For skilled and unskilled labour separately in the right panel the slopes are 0.73 and 0.68, respectively, and the R^2s are 0.96 and 0.92, respectively. The results without productivity adjustments are very similar. The OLS line of best fit is displayed as is its slope (standard error) and R^2. For the purposes of display Malta is not shown in either panel: It lies on the line of best fit but is far to the bottom left.

market clearing equation $\sum_g d_{fgi}Q_{gi} = V_{fi}$. Multiplying through by λ^V_{fi} yields $\sum_g \widetilde{d}_{fgi}Q_{gi} = \widetilde{V}_{fi}$. This means that $F_{fi} = V_{fi} - s_iV_{fw}$ iff

$$\widetilde{F}_{fi} = \widetilde{V}_{fi} - s_i\widetilde{V}_{fw} \tag{29}$$

where $\widetilde{F}_{fi}$ is computed in the same way as F_{fi} but using $\widetilde{d}_{fgi}$ in place of d_{fgi}. See Trefler (1993). This prediction sums U.S. and Indian labour only after measuring them in comparable, productivity-adjusted units. The right panels of figure 6 repeat the left panels, but now plotting $\widetilde{F}_{fi}/\widetilde{V}_{fi}$ against $(\widetilde{V}_{fi} - s_i\widetilde{V}_{fw})/\widetilde{V}_{fi}$. This does not change our conclusions.

8.4. The Role of Trade Costs and Preferences

The preceding sections explored the determinants of the supply side of the Vanek equation. However, we know from Figure 6 that the Vanek equation display an abundance of missing trade even if we fit the supply side perfectly by using actual data.

We now turn to the quantitative model to ask and answer two questions. First, to what extent is the failure of the Vanek prediction due to trade costs as opposed to international preference differences. Corollary 1 established the new result that, as an identity, the failure of the Vanek prediction must be due some mix of these two factors. To answer this we switch off trade costs ($\tau_{gi,j} = 1$ for all g, i and j) and re-simulate the model to obtain model-generated data for $\widetilde{F}_{Si}/\widetilde{V}_{Si} - \widetilde{F}_{Ui}/\widetilde{V}_{Ui}$ and $(\widetilde{V}_{Si} - s_i\widetilde{V}_{Sw})/\widetilde{V}_{Si} - \widetilde{F}_{Ui}(\widetilde{V}_{Ui} - s_i\widetilde{V}_{Uw})/\widetilde{V}_{Ui}$. The left panel of Figure 7 plots this. The fit is almost perfect, which means that *the failure of the Vanek prediction is entirely* *driven by the presence of trade costs and is not at all driven by the presence of international preference differences.*[34]

Second, Trefler and Zhu (2010) observe that the failure of the Vanek equation is largely driven by just a few sectors, namely, Agriculture, Government Services, and Construction. We can use our quantitative model to investigate this claim in general equilibrium. In particular, we ask what would happen in general equilibrium if all trade costs in Government Services were eliminated. We chose Government Services because System of National Accounts manuals instruct national statistical agencies to define Government Services as non-tradable government services.[35] We thus eliminate all trade costs for Government Services ($\tau_{\text{Govt}\,i,j} = 1$), re-simulate the model and plot as in the left panel of figure 7. The results appear in the right panel. Remarkably, the slope rises from 0.18 to 0.64, that is, a large chunk of missing trade is explained solely by a single non-traded sector.

9. Conclusion

The answers to many key questions in international trade depend on the size of the components of two decompositions:

1. How countries absorb their endowments of skilled and unskilled labour decomposes into contributions from (*a*) between-industry differences in output mix and (*b*) within-industry differences in skill intensities.
2. Why skill intensities vary across countries decomposes into contributions from cross-country differences in (*a*) relative wages and (*b*) skill-biased, factor-augmenting technology.

We provided evidence both from actual data and from a quantitative trade model that the output-mix component is small, that the relative wage and factor-augmenting technology components are large, and that some of the relative wage component is induced by the indirect general equilibrium impacts on wages of factor-augmenting international technology differences.

Along the way we developed a new method of estimating factor-augmenting technology differences. Surprisingly to us, we found that our estimated technology differences are very similar to those obtained using a one-sector aggregate model as in Caselli and Coleman (2006). This is consistent with our finding of small output-mix effects.

We also found both in the data and the quantitative trade model that wages of skilled relative to unskilled labour are highly and negatively correlated with endowments of skilled relative to unskilled labour. Further, this relationship is extremely tight when wages and endowments are measured in productivity-adjusted units ($R^2 = 0.99$). This implies that relative wages are

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[34] We obtain the exact same conclusion from plotting $\widetilde{F}_{fi}/\widetilde{V}_{fi}$ against $(\widetilde{V}_{fi} - s_i\widetilde{V}_{fw})/\widetilde{V}_{fi}$ for $f = S,U$. We also obtain the exact same result without the productivity adjustment.

[35] More exactly, System of National Accounts manuals instruct national statistical agencies to exclude from this sector all government services that are sold via market transactions. By way of example, Canadian postal services are sold to the public but police services are not so that Government Services excludes the post office but not the police. Since by this definition Government Services are not sold on markets, they are nontraded — we do not see California state troopers patrolling the streets of São Paolo.

sensitive to domestic endowments and that factor price equalization fails in both physical and productivty-adjusted terms. This too is consistent with our small measured output-mix effects. In conclusion, for the question of how countries absorb their endowments, factor-augmenting international technology differences and wages play a critical role while output mix plays a more modest role.

Appendix

Appendix A. Expression for Expenditure

Proof of Equation (8)***:*** Part 1: Country j's expenditure power is $E_j \equiv w_{Sj}V_{Sj} + w_{Uj}V_{Uj} + D_j$ i.e., income from primary factors plus exogenous deficit spending. From the cost function (equation 5), primary factor income generated in (h,j) is a fraction γ_{hj}^V of costs and hence of sales Q_{hj}.[36] Hence primary income in j is $\sum_{h=1}^G \gamma_{hj}^V\, Q_{hj}$ and $E_j = \sum_h \gamma_{hj}^V\, Q_{hj} + D_j$.

Part 2: The representative consumer in country j spends a fraction γ_{gj}^U of E_j on g and a fraction $\pi_{gi,j}$ of $\gamma_{gj}^U\, E_j$ on g sourced from i. Thus, the country j consumer spends $\pi_{gi,j}\, \gamma_{gj}^U\, E_j$ on (g,i). Substituting in the part 1 expression for E_j, the country j consumer spends $\pi_{gi,j}\, \gamma_{gj}^U\, (\sum_h \gamma_{hj}^V\, Q_{hj} + D_j)$ on (g,i).

Part 3: Country j producers of h have sales and hence costs of Q_{hj}. A fraction $\gamma_{g,hj}^I$ of Q_{hj} is spent on input g and a fraction $\pi_{gi,j}$ of $\gamma_{g,hj}^I\, Q_{hj}$ is spent on g sourced from i. Since country j producers of h spend $\pi_{gi,j}\, \gamma_{g,hj}^I\, Q_{hj}$ on (g,i), country j producers together spend $\sum_h \pi_{gi,j}\, \gamma_{g,hj}^I\, Q_{hj}$ on (g,i).

Part 4: Collecting the conclusions of parts 2 and 3, country j consumer and producer expenditures on (g,i) are

$$E_{gi,j} \;=\; \textstyle\sum_h \pi_{gi,j}\, \gamma_{g,hj}^I\, Q_{hj} + \pi_{gi,j}\, \gamma_{gj}^U\, \left(\sum_h \gamma_{hj}^V\, Q_{hj} + D_j\right)$$

Equation (8) follows immediately. ■

Appendix B. Primary Factor Input Demands

Proof of Equation (11) By Shephard's lemma, ω_g's per unit demand for primary factor f is just the derivative of the unit cost function i.e., the derivative of $c_{gi}/z_{gi}(\omega_g)$. Hence ω_g's total demand for f is $V_{fgi}(\omega_g) \equiv \{\partial[c_{gi}/z_{gi}(\omega_g)]/\partial w_{fi}\}q_{gi}(\omega_g)$. Rearranging, $V_{fgi}(\omega_g) = [\partial c_{gi}/\partial w_{fi}](c_{gi})^{-1}\{[c_{gi}/z_{gi}(\omega)]q_{gi}(\omega_g)\}$. Integrating this over ω_g generates demand for f by all varieties in gi, $V_{fgi} \equiv \int V_{fgi}(\omega_g)\, d\omega_g = [\partial c_{gi}/\partial w_{fi}](c_{gi})^{-1} \int [c_{gi}/z_{gi}(\omega)]q_{gi}(\omega_g)\, d\omega_g$. But the integral is just sales Q_{gi}. Hence, $V_{fgi} = [\partial c_{gi}/\partial w_{fi}](c_{gi})^{-1}Q_{gi}$. Hence demand for f by all varieties in (g,i) per dollar of sales of (g,i) is $d_{fgi} \equiv V_{fgi}/Q_{gi} = [\partial c_{gi}/\partial w_{fi}]/c_{gi}$. From the unit cost functions (equations 1 and 5), $[\partial c_{gi}/\partial w_{fi}]/c_{gi} = [\partial c_{gi}^V/\partial w_{fi}]/c_{gi}^V$. Using equation (1) to calculate $[\partial c_{gi}^V/\partial w_{fi}]/c_{gi}^V$ yields equation (11). ■

Appendix C. List of Countries and Industries:

List of Countries: We include the following 39 countries from the 2013 vintage of the WIOD data base: Australia[5], Austria[1,2,3], Belgium[1,2,3], Brazil, Bulgaria, Canada[4], China[6,8], Cyprus[1,2,3], Czech Republic[1,2,3], Denmark[1,2,3], Estonia[1,2,3], Finland[1,2,3], France[1,2,3], Germany[1,2,3], Great Britain[1,2,3], Greece[1,2,3], Hungary[1,2,3], India[6], Indonesia[8], Ireland[1,2,3], Italy[1,2,3], Japan[7], Korea, Latvia[1,2,3], Lithuania[1,2,3], Malta[1,2,3], Mexico[2,4,7], Netherlands[1,2,3], Poland[1,2,3], Portugal[1,2,3], Romania, Russia, Slovakia[1,2,3], Slovenia[1,2,3], Spain[1,2,3] Sweden, Taiwan, Turkey[3], and USA[4,5].

There is a EU customs union that takes a value of one for trade between the following countries and zero otherwise: Austria, Belgium, Cyprus, Czech Republic, Denmark, Germany, Spain,

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[36] Recall that all the γs in this paper are Cobb-Douglas exponents.

Estonia, Finland, France, Great Britain, Greece, Hungary, Ireland, Italy, Lithuania, Latvia, Malta, The Netherlands, Poland, Portugal, Slovakia, Slovenia.

There is another but single dummy that takes a value of one if two countries are both members of a preferential trade agreement in 2006. Membership is represented by the following superscripts above the country names as follows: (1): The European Union, (2): the EU-Mexico Trade Agreement, (3): the EU-Turkey Trade Agreement, (4): NAFTA, (5): the Australia-United States Trade Agreement, (6): the China-India Trade Agreement, (7): the Japan-Mexico Trade Agreement, (8): the China-Indonesia Trade Agreement.

We do not use Luxembourg in our analysis because it does not report any production in some industries and because its economy is highly distorted by its tax-haven policies. We also dropped the rest of the world because it was not obvious how to calculate objects such as bilateral distance.

List of Industries and NACE codes: We use the following industries: Agriculture (AtB); Mining (C); Food, Beverages, Tobacco (15t16); Textiles and Textile Products (17t18); Leather and Footwear (19); Wood and Products of Wood (20); Pulp, Paper, Printing, and Publishing (21t22); Coke, Refined Petroleum, and Nuclear Fuel (23); Chemicals (24); Rubber and Plastics (25); Non-Metallic Minerals (26); Basic and Fabricated Metals (27t28); Machinery, nec. (29); Electrical and Optical Equipment (30t33);Transport Equipment (34t35); Manufacturing, nec. (36t37); Electricity, Gas, Water Supply (E); Construction (F); Wholesale and Retail Trade (50,51,52); Hotels and Restaurants (H); Transport (60,61,62,63,64); Finance, Insurance, Real Estate (J,70,71t74); Government Services (L,M,N,O,P). Relative to the WIOD data base, we aggregated up slightly to make our results comparable to previous HOV (Davis and Weinstein (2001)) and more recent Ricardian (Caliendo and Parro (2015)) study. Unlike Caliendo and Parro (2015) and Levchenko and Zhang (2016), we allow for services that are traded subject to iceberg costs that are allowed to differ from manufacturing. For comparability to older papers that also allow for services trade (e.g. Davis and Weinstein (2001) pg. 1446, Trefler and Zhu (2010) pg. 204), we aggregate certain services. Specifically, we aggregate "Sale, Maintenance, and Repair of Motor Vehicles", "Wholesale Trade", and "Retail Trade" into "Wholesale and Retail Trade." We also aggregate "Inland Transport", "Water Transport", "Air Transport", and "Other Supporting and Auxiliary Transport Activities" into "Transport"; "Financial Intermediation", "Real Estate Activities", and "Renting of Machinery and Equipment and Other Business Activities" into "FIRE"; and "Public Admin", "Education", "Health and Social Work", and "Other Community, Social, and Personal Services" into "Government Services." We drop "Private Households with Employed Persons."

Appendix D. Details of Calibration and Simulation

1. Calibration of the Productivity Parameters λ^V_{fi} and λ^R_{gi}: If the γ^V_{gi} and $\gamma^I_{h,gi}$ were independent of i then we could follow Levchenko and Zhang (2012) in using the estimates of $c_{gi}/c_{g,\text{us}}$ to solve for the $\lambda^R_{gi}/\lambda^R_{g,\text{us}}$. Instead, we appeal to the following generalization of their approach.

Lemma A1

$$\left(\frac{\lambda^R_{gi}}{\lambda^R_{gus}}\right)^{\frac{1}{\gamma^V_{gi}}} \lambda^V_{Ui} = \left[\frac{c_{gi}}{c_{gus}}\right]^{\frac{-1}{\gamma^V_{gi}}} \left[\left(\frac{\kappa_{gi}}{\kappa_{gus}}\right)^{\frac{1}{\gamma^V_{gi}}} \left(\frac{\{\sum_f \alpha_{fg}(w_{fi}\lambda^V_{Ui}/\lambda^V_{fi})^{1-\sigma}\}^{\frac{1}{1-\sigma}}}{\{\sum_f \alpha_{fg}(w_{fus})^{1-\sigma}\}^{\frac{1}{1-\sigma}}}\right) \prod_{h=1}^{G}\left(\frac{c_{hi}}{c_{hus}}\right)^{\frac{\gamma^I_{h,gi}}{\gamma^V_{gi}}}\right]$$

$$\prod_{h=1}^{G}\left(\frac{\pi^{1/\theta_h}_{hi,i}}{\pi^{1/\theta_h}_{h\,us,us}}\right)^{\frac{\gamma^I_{h,gi}}{\gamma^V_{gi}}} \left(\{\textstyle\sum_f \alpha_{fg} w^{1-\sigma}_{fus}\}^{\frac{1}{1-\sigma}}\right)^{1-\frac{\gamma^V_{gus}}{\gamma^V_{gi}}} \tag{30}$$

and

$$(\lambda^R_{gus})^{1/\gamma^V_{gus}} = \left[(\pi_{gus,us})^{1/\theta_g}\kappa_g\kappa_{gus}\right]^{1/\gamma^V_{gus}}\left[\sum_f \alpha_{fg}(w_{fus})^{1-\sigma}\right]^{1/1-\sigma} . \tag{31}$$

Proof Plug c^V_g of equation (1) into the equation (5) expression for c_{gi}. Then divide through by the corresponding expression for $c_{g\text{us}}$ to yield

$$\frac{c_{gi}}{c_{g\text{us}}} = \frac{\lambda^R_{g\text{us}}}{\lambda^R_{gi}}\frac{\kappa_{gi}}{\kappa_{g,\text{us}}}\left(\frac{c^V_{gi}}{c^V_{g\text{us}}}\right)^{\gamma^V_{gi}}(c^V_{g\text{us}})^{\gamma^V_{gi}-\gamma^V_{g\text{us}}}\prod\nolimits_h\left(\frac{P_{hi}}{P_{h,\text{us}}}\right)^{\gamma^I_{h,gi}}\prod\nolimits_h P_{h\text{us}}^{\gamma^I_{h,gi}-\gamma^I_{h,g\text{us}}} . \tag{32}$$

Substituting equation (7) with $j = i$ into equation (6) yields

$$P_{hi} = \kappa_h c_{hi}\pi^{1/\theta_h}_{hi,i} . \tag{33}$$

Hence

$$\frac{P_{hi}}{P_{h\text{us}}} = \frac{c_{hi}}{c_{h\text{us}}}\frac{\pi^{1/\theta}_{hi,i}}{\pi^{1/\theta}_{h\text{us},\text{us}}} . \tag{34}$$

We choose units so that $P_{h\text{us}} = 1$.[37] Hence from equation (33)

$$c_{g\text{us}} = k_g^{-1}\pi^{-1/\theta}_{g\text{us},\text{us}} . \tag{35}$$

From equation (1) and the fact that $\lambda^V_{g\text{us}} = 1$ for $f = S,U$:

$$\frac{c^V_{gi}}{c^V_{g\text{us}}} = \frac{1}{\lambda^V_{Ui}}\left(\frac{\sum_f \alpha_{fg}\left(w_{fi}\lambda^V_{Ui}/\lambda^V_{fi}\right)^{1-\sigma}}{\sum_f \alpha_{fg}\left(w_{f\text{us}}\right)^{1-\sigma}}\right)^{1/(1-\sigma)} . \tag{36}$$

Equation (30) is derived as follows. Into equation (32) plug (34), then (36), then $P_{h\text{us}} = 1$, and then (35). Rearranging the result yields equation (30). To derive equation (31), start with (36) and substitute out $c_{g,\text{us}}$ using (5) evaluated at $i = $ us. The result is a function of $\lambda^R_{g\text{us}}$ and, after setting $P_{h\text{us}} = 1$, can be rearranged to yield equation (31). ■

We can now explain how we calculate the productivity parameters. We first show that all of the variables on the right side of equations (30) and (31) are known. α_{fg}, w_{fi}, $\pi_{gi,i}$, all of the γs and κ_{gi} are from WIOD. $\theta = 5.03$ and $\rho = 4$ pin down $\kappa_g \equiv \mathit{\Gamma}((1+\theta-\rho)/\theta)^{1/(1-\rho)}$. When $f = U$ we have $\overset{V}{\lambda}_{Ui}/\overset{V}{\lambda}_{fi} = 1$ and when $f = S$ equation (16) gives $\overset{V}{\lambda}_{Ui}/\overset{V}{\lambda}_{fi}$. Let $\widehat{\delta}'_{gi}$ be the estimate of $\delta_{gi} - \delta_{g\text{us}}$ in equation (14). Then from equation (13), $c_{gi}/c_{g\text{us}} = \exp(-\widehat{\delta}'_{gi}/\theta)$. Thus, everything on the right side of equations (30) and (31) are known.

Equations (16) and (30) pin down $\lambda^V_{Si}/\lambda^V_{Ui}$ and $(\lambda^R_{gi})^{1/\gamma^V_{gi}}\lambda^V_{Ui}$, respectively, but not λ^V_{Si} and $(\lambda^R_{gi})^{1/\gamma^V_{gi}}$. To understand why, note that the λ^R_{gi} and λ^V_{fi} enter the cost function multiplicatively rather than separately. From equation (5), they enter as $(\lambda^R_{gi})^{1/\gamma^V_{gi}}\lambda^V_{fi}$. Absolute advantage therefore pins down the product of the $(\lambda^R_{gi})^{1/\gamma^V_{gi}}$ and λ^V_{fi}, but not the level of each separately. This is

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[37] This is a choice of quantity units, not a price normalization. To see this note that in international productivity comparisons each industry must have a productivity normalization. A standard one is $\lambda^R_{g\text{us}} = 1$ for each g. This is needed because productivity converts input bundles into output bundles and, since input and output bundles are not measured in the same units (e.g., labour and kilograms), the base level of productivity is not unit free. With our WIOD data, which is measured in U.S. dollars, the choice of units for quantities that is easiest to understand is $P_{g\text{us}} = 1$ for each g. That is, a unit quantity of g is the amount needed to produce a dollar of revenue in g. Note that the choice of units $P_{h\text{us}} = 1$ is not the same as a normalization of prices. While we impose $P_{g\text{us}} = 1$ in the benchmark equilibrium, the $P_{g\text{us}}$ are not unity in the counterfactuals i.e., the $P_{g\text{us}}$ adjust in equilibrium. We could alternatively impose $\lambda^R_{g\text{us}} = 1$ for all g and then work out the implied expressions for the P_{gi} in the benchmark equilibrium.

why equations (16) and (30) only pin down $\lambda^V_{Si}/\lambda^V_{Ui}$ and $(\lambda^R_{gi})^{1/\gamma^V_{gi}}\lambda^V_{Ui}$. Clearly we must normalize either the $(\lambda^R_{gi})^{1/\gamma^V_{gi}}$ or the λ^V_{fi}. Given our focus on endowments it is convenient to normalize the former. From equation (30) a convenient normalization is $\sum_g(Q_{gi}/\sum_{g'}Q_{g'i})(\lambda^R_{gi}/\lambda^R_{g,\text{us}})^{1/\gamma^R_{gi}} = 1$. Applying this normalization by multiplying equation (30) through by $Q_{gi}/\sum_{g'}Q_{g'i}$ and summing across g pins down λ^V_{Ui} and hence all of the productivity parameters.

Finally, we relate our approach to Malmberg (2017). Malmberg uses the translog identity based on (Caves, Christensen and Diewert, 1982). Unfortunately, the assumptions underlying the translog identity are that (1) the cost function must be translog and (2) the first-order translog coefficients must be internationally identical. (1) is not satisfied because CES is not translog.

2. Simulation Algorithm: This section describes our algorithm that solves for all the endogenous variables. The primitives that feed into the algorithm are data on endowments $\{V_{fi}\}_{fi}$ and trade deficits $\{D_i\}_i$, the calibrated $\{\lambda^V_{fi}\}_{fi}$, $\{\lambda^R_{gi}\}_{gi}$, $\{\tau_{gi,j}\}_{gij}$, $\{\gamma^U_{gi}\}_{gi}$, $\{\gamma^V_{gi}\}_{gi}$, and $\{\gamma^I_{h,gi}\}_{hgi}$, and σ, θ, and ρ (from external sources).

1. Consider a $N*K$ matrix of factor prices $\{w_{fi}\}$ up to some normalization which we take to be $w_{U\text{us}} = 1$. Solve for a candidate matrix of c^V_{gi} as in equation (1).
2. Guess a matrix of values $\{P_{gi}\}$.
    (a) Given $\{P_{gi}\}$, solve for the matrix of candidate unit costs $\{c_{gi}\}$ using equation (5).
    (b) Solve for a new set of prices $\{P_{gi}\}$ using equation (6).
    (c) Iterate until the new set of $\{P_{gi}\}$ from part 2b is the same as the guess from part 2.
3. Calculate the expenditure shares consistent with these prices $\pi_{gi,j}$ as in equation (7).
4. Calculate aggregate expenditures $E_i = w_{Ui}V_{Ui} + w_{Ui}V_{Ui} + D_i$.
5. Solve for the matrix of $\{Q_{gi}\}$ using equations (8)–(9).
6. Using factor market clearing (12) and equation (11), calculate total demand for each factor. If labour demand is too high relative to $\{V_{fi}\}$, adjust relative wages upward. If labour demand is too low relative to $\{V_{fi}\}$, adjust relative wages downward.
7. Iterate on $\{w_{fi}\}$ until labour market clearing holds.

3. Simulation of World Input-Output Table, Trade, and Consumption: Input-output tables report data that are aggregated up from varieties to goods (industries) and that are in values. Recall that $C_{gi,j}$ is the value of country j's consumption of (g,i), $M_{gi,j}$ is the value of country j's imports of (g,i), X_{gi} is the value of country i's exports of g, and $b_{gi,hj}$ is the value of intermediate purchases of (g,i) per dollar of (h,j) output. The following lemma shows how each of these is aggregated up to the industry level and relates each of these back to primitives of the model. It thus shows how each is simulated.

Lemma A2 *(1)* $C_{gi,j} = \pi_{gi,j}\gamma^U_{gj}\left[\sum_{h=1}^G \gamma^V_{hj}Q_{hj} + D_j\right]$ *. (2)* $M_{gi,j} = \pi_{gi,j}\sum_{h=1}^G(\gamma^I_{g,hj} + \gamma^U_{gj}\gamma^V_{hj})Q_{hj} + \pi_{gi,j}\gamma^U_{gj}D_j$ *for* $j \neq i$ *. (3)* $X_{gi} = \sum_{j\neq i} M_{gi,j}$ *. (4)* $b_{gi,hj} = \pi_{gi,j}\gamma^I_{g,hj}$ *.*

Proof: (1) $C_{gi,j}$ is country j's consumption of (g,i). The result follows from part 2 of Appendix A. (2) $M_{gi,j}$ is the value of country j's imports of (g,i), which is just j's expenditures on (g,i) i.e., which is $E_{gi,j}$ of equation (8). (3) X_{gi} is country i's exports of g, which is the sum over importers $j \neq i$ of their imports $M_{gi,j}$. (4) $b_{gi,hj}$ is the value of intermediate inputs of (g,i) required per dollar of (h,j) output. From the cost function (equation 5), the production of (g,i) uses $\gamma^I_{h,gi}$

dollars of intermediate input h per dollar of output. Swapping indexes, the production of (h,j) uses $\gamma^I_{g,hj}$ dollars of intermediate input g per dollar of output. A fraction $\pi_{gi,j}$ of this g is sourced from i. Hence, purchases of intermediate (g,i) per dollar of (h,j) output is $\pi_{gi,j}\,\gamma^I_{g,hj}$. ■

To simulate the variables in lemma A2 note that the γs and D_j are primitives and the $\pi_{gi,j}$ and Q_{gi} are from outputted from the simulation algorithm (steps 3 and 5, respectively). Thus, the right-hand side of each of the equations in lemma A2 is known. These equations supply the model-generated values of $b_{gi,hj}$, $M_{gi,j}$, X_{gi}, and $C_{gi,j}$.

Part 4 of the lemma endogenizes input-output tables, which is closely related to Caliendo et al. (2017), Antràs and de Gortari (2017) and Antràs and Chor (2019). The endogeneity stems from the fact that the $\pi_{gi,j}$ depend on all prices i.e., on all the w_{fi} and P_{gi}. In addition, we endogenize the primary-input requirements table whose typical element d_{fgi} depends on all of the w_{fi} (equation 11).

In section 8.1 we introduced $\mathbf{T}_i = (\mathbf{I}-\mathbf{B})\mathbf{Q}_i - \mathbf{C}_i$ (eqn. 26). $\mathbf{Q}_i$, $\mathbf{C}_i$, and $\mathbf{T}_i$ are the ith columns of

$$\mathbf{Q} \equiv \begin{bmatrix} \mathbf{Q}_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{Q}_N \end{bmatrix}, \qquad \mathbf{C} \equiv \begin{bmatrix} \mathbf{C}_{11} & \cdots & \mathbf{C}_{N1} \\ \vdots & \ddots & \vdots \\ \mathbf{C}_{1N} & \cdots & \mathbf{C}_{NN} \end{bmatrix},$$

$$\mathbf{T} \equiv \begin{bmatrix} \mathbf{X}_1 & -\mathbf{M}_{21} & \cdots & -\mathbf{M}_{N1} \\ -\mathbf{M}_{12} & \mathbf{X}_2 & \cdots & -\mathbf{M}_{N2} \\ \vdots & \vdots & \ddots & \vdots \\ -\mathbf{M}_{1N} & -\mathbf{M}_{2N} & \cdots & \mathbf{X}_N \end{bmatrix} \text{ and } \mathbf{B} \equiv \begin{bmatrix} \mathbf{B}_{11} & \mathbf{B}_{12} & \cdots & \mathbf{B}_{1N} \\ \mathbf{B}_{21} & \mathbf{B}_{22} & \cdots & \mathbf{B}_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{B}_{N1} & \mathbf{B}_{N2} & \cdots & \mathbf{B}_{NN} \end{bmatrix}$$

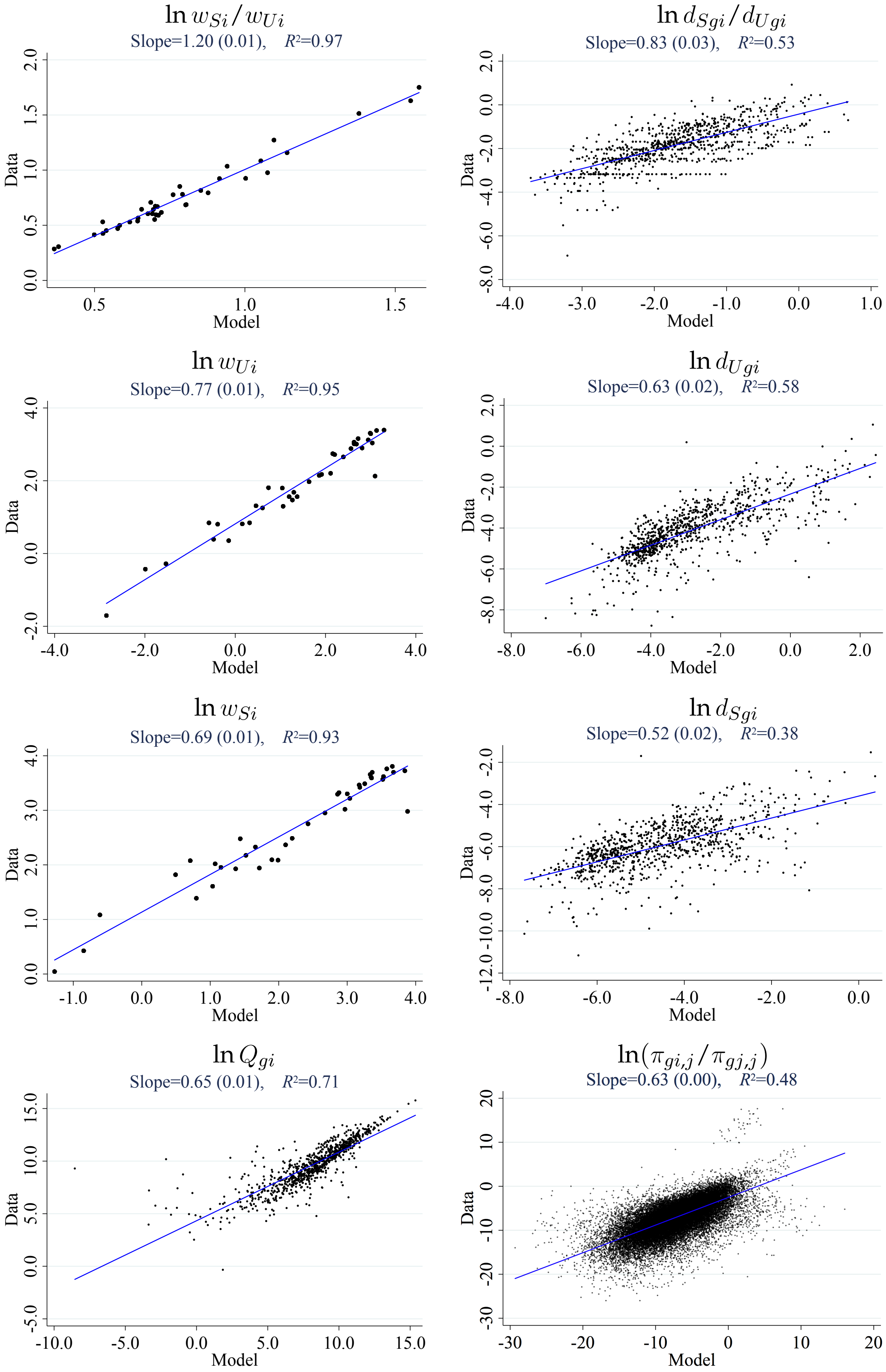
where $\mathbf{Q}_i$, $\mathbf{C}_{ij}$, $\mathbf{M}_{ij}$, and $\mathbf{X}_i$ are $G \times 1$ vectors whose gth elements are Q_{gi}, $C_{gj,i}$, $M_{gj,i}$, and X_{gi}, respectively. $\mathbf{B}_{ij}$ is a $G \times G$ matrix whose (g,h)-th element is $b_{gi,hj}$. The dimensions of $\mathbf{Q}$, $\mathbf{C}$, and $\mathbf{T}$ are $NG \times N$ and $\mathbf{B}$ is $NG \times NG$. Global value chains are captured by the $\mathbf{B}_{ij}$. The related trade flows are in the bilateral world trade flows matrix $\mathbf{T}$. The fundamental input-output equation is $\mathbf{Q} = \mathbf{BQ} + \mathbf{C} + \mathbf{T}$ or $\mathbf{T} = (\mathbf{I}-\mathbf{B})\mathbf{Q} - \mathbf{C}$.

4. Model Fit: Figure A1 illustrates that the model fits the data quite respectably. Each panel is a different endogenous variable of interest and the actual data appear on the vertical axis while the model-generated prediction of that data appears on the horizontal axis. In the first column of panels, the first three rows display, respectively, $\ln w_{Si}/w_{Ui}$, $\ln w_{Si}$ and $\ln w_{Ui}$. The line of best fit is displayed as is its slope (standard error) and R^2. The model almost perfectly captures cross-country differences in skill premia. However, the model also systematically overstates the premium in every country: The best fit line is about 0.4 log points above the diagonal. This illustrates a feature of our calibration: We could bring the line to the diagonal by setting $\sigma = 1.1$; however, external studies rarely estimate such a low value of σ so that we would be overfitting the model by choosing σ to improve our fit. In the second column of panels, the first three rows display, respectively, $\ln d_{Sgi}/d_{Ugi}$, $\ln d_{Sgi}$ and $\ln d_{Ugi}$. The bottom panels plot $\ln Q_{gi}$ and $\ln(\pi_{gi,j}/\pi_{gj,j})$. The points far from the OLS line of best fit tend to be agriculture and mining.

Appendix E. How Do Economies Adjust to Endowments? (Derivations)

Proof of Equation (21)***:*** Divide equation (12) with $f = S$ by equation (12) with $f = U$. Substitute out the d_{fgi} using equation (11) to obtain equation (21) with $[c^V_{gi}(w_{Si}, w_{Ui})]^{\sigma-1}$ replaced by $\sum_f \alpha_{fg}\left(w_{fi}/\lambda^V_{fi}\right)^{1-\sigma}$. By equation (1) the two are equal. ■

Figure A1: Model Fit



$\ln w_{Si}/w_{Ui}$
Slope=1.20 (0.01), R^2=0.97

$\ln d_{Sgi}/d_{Ugi}$
Slope=0.83 (0.03), R^2=0.53

$\ln w_{Ui}$
Slope=0.77 (0.01), R^2=0.95

$\ln d_{Ugi}$
Slope=0.63 (0.02), R^2=0.58

$\ln w_{Si}$
Slope=0.69 (0.01), R^2=0.93

$\ln d_{Sgi}$
Slope=0.52 (0.02), R^2=0.38

$\ln Q_{gi}$
Slope=0.65 (0.01), R^2=0.71

$\ln(\pi_{gi,j}/\pi_{gj,j})$
Slope=0.63 (0.00), R^2=0.48

Proof of Equation (23)***:*** The proof starts by totally differentiating $\ln(\sum \widetilde{d}_{Sgi} Q_{gi}) = \ln \widetilde{V}_{Si}$ to obtain

$$\left[\frac{\widetilde{d}_{Sgi} Q_{gi}}{\sum \widetilde{d}_{Sgi} Q_{gi}} \Delta \ln \widetilde{d}_{Sgi} + \frac{\widetilde{d}_{Sgi} Q_{gi}}{\sum \widetilde{d}_{Sgi} Q_{gi}} \Delta \ln Q_{gi} \right] = \Delta \ln \widetilde{V}_{Si} \ .$$

Repeating this for $\ln(\sum \widetilde{d}'_{Sgi} Q'_{gi}) = \ln \widetilde{V}'_{Si}$ and averaging the results yields $\sum_{g=1}^{G} \theta_{Sgi} \Delta \ln Q_{gi} + \sum_{g=1}^{G} \theta_{Sgi} \Delta \ln \widetilde{d}_{Sgi} = \Delta \ln \widetilde{V}_{Si}$. Repeating for $f = U$ and differencing across S and U yields the above. While this is a finite approximation of the derivatives, the approximation is 99.9% accurate. ■

Appendix F. Partial Equilibrium Exercises

Holding wages constant, this exercise solves for unit input requirements $\overline{d}_{fgi}^{D}$ given counterfactual values of λ_{fi}^{V} holding w_{fi} and P_{gi} constant. Where primes denote counterfactual values, unit input requirements can be solved as follows:

$$\overline{d}_{fgi}^{D} \equiv c_{gi}^{D} \left(\gamma_{gi}^{V} / \lambda_{fi}^{V'} \right) \left[\alpha_{fg} \left(w_{fi} / \lambda_{fi}^{V'} \right)^{-\sigma} \right] \Big/ \left[\sum_{f'} \alpha_{f'g} \left(w_{f'i} / \lambda_{f'i}^{V'} \right)^{1-\sigma} \right]$$

where

$$c_{gi}^{D} \equiv \frac{\kappa_{gi}}{\lambda_{gi}^{R}} \left\{ \left[\sum_{f} \alpha_{fg} \left(w_{fi} / \lambda_{fi}^{V\,\prime} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \right\}^{\gamma_{gi}^{V}} \prod_{h=1}^{G} (P_{hi})^{\gamma_{h,gi}^{I}} \ .$$

To solve for the partial equilibrium effect of changes in productivity on dollar input requirements allowing price indexes to change but holding wages constant $\overline{d}_{fgi}^{P}$, we solve for the following system of 2NG equations

$$c'_{gi} = \frac{\kappa_{gi}}{\lambda_{gi}^{R}} \left\{ \left[\sum_{f} \alpha_{fg} \left(w_{fi} / \lambda_{fi}^{V\,\prime} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \right\}^{\gamma_{gi}^{V}} \prod_{h=1}^{G} (P'_{hi})^{\gamma_{h,gi}^{I}} \ .$$

$$P'_{gi} = \kappa_{g} \left[\sum_{j=1}^{N} \left(c'_{gj} \tau_{gj,i} \right)^{-\theta_{g}} \right]^{-1/\theta_{g}}$$

holding factor prices constant at their baseline solution. $\overline{d}_{fgi}^{P}$ is then calculated taking these into account.

Appendix G. The Vanek Equation

Proof of Theorem 1 Pre-multiplying equation (26) by $\mathbf{A}_f$ yields $\mathbf{A}_f \mathbf{T} = \mathbf{A}_f (\mathbf{I}_{NG} - \mathbf{B}) \mathbf{Q} - \mathbf{A}_f \mathbf{C} = \mathbf{D}_f \mathbf{Q} - \mathbf{A}_f \mathbf{C} = \begin{bmatrix} V_{f1} & \cdots & V_{fN} \end{bmatrix} - \mathbf{A}_f \mathbf{C}$. Consider column i of this equation, namely,

$$\mathbf{A}_f \mathbf{T}_i = V_{fi} - \mathbf{A}_f \mathbf{C}_i \tag{37}$$

where $\mathbf{T}_i$ and $\mathbf{C}_i$ are the ith columns of T and C, respectively. Hence

$$\mathbf{A}_f \Sigma_j \mathbf{T}_j = \Sigma_j V_{fj} - \mathbf{A}_f \Sigma_j \mathbf{C}_j. \tag{38}$$

Consider each of the three terms in this equation. $V_{fw} \equiv \Sigma_j V_{fj}$ is the world endowment of f. Recall that $\mathbf{T}_j$ is composed of blocks of $G \times 1$ matrices. Let $\mathbf{T}_{ij}$ be the ith block of $\mathbf{T}_j$. Then by inspection of the definition of $\mathbf{T}$ together with globally balanced trade, $\Sigma_j \mathbf{T}_{ij} = \mathbf{X}_i - \Sigma_j \mathbf{M}_{ji} = \mathbf{0}_G$ where $\mathbf{0}_G$ is the $G \times 1$ vector of zeros. Hence $\Sigma_j \mathbf{T}_j = \mathbf{0}_{NG}$ where $\mathbf{0}_{NG}$ is the $NG \times 1$ vector of zeros. Recall that $\mathbf{C}_w \equiv \sum_j \mathbf{C}_j$. Thus, equation (38) can be written as $0 = V_{fw} - \mathbf{A}_f \mathbf{C}_w$ or $0 = s_i V_{fw} - \mathbf{A}_f (s_i \mathbf{C}_w)$. Subtracting this from equation (37) yields $F_{fi} = V_{fi} - s_i V_{fw} - \mathbf{A}_f \left(\mathbf{C}_i - s_i \mathbf{C}_w \right)$. ■

Proof of Corollary 1 For notational simplicity normalize world expenditures to unity so that s_j is j's total expenditures. γ^U_{gj} is the fraction of j's final consumption expenditure allocated to g. $\gamma^U_{gj}\, s_j$ is what j spends on final consumption of g. $\pi_{gi,j}\, \gamma^U_{gj}\, s_j$ is what j spends on final consumption of (g,i). Hence $C_{gi,j} = \pi_{gi,j}\, \gamma^U_{gj}\, s_j$. Internationally identical preferences means that $\gamma^U_{gj} = \gamma^U_g$ for all g and j. Zero trade costs means $\tau_{gi,j} = 1$ for all (g,i) and j and so implies that $\pi_{gi,j}$ is constant across all j for a given (g,i) (see equation 7). Call this π_{gi}. Hence, $C_{gi,j} = \pi_{gi}\, \gamma^U_g\, s_j$. Summing this over j and using $\sum_j s_j = 1$ yields $C_{gi,w} = \pi_{gi}\, \gamma^U_g$ so that $s_j C_{gi,w} = \pi_{gi}\, \gamma^U_g\, s_j$. This establishes $C_{gi,j} = s_j C_{gi,w}$ or, in matrix notation, $\mathbf{C}_j = s_j \mathbf{C}_w$. Hence $\mathbf{A}_f \left(\mathbf{C}_i - s_i \mathbf{C}_w \right) = 0$. $F_{fi} = V_{fi} - s_i \sum_j V_{fj}$ follows from equation (28). ■

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Online Appendix to

“How Do Endowments Determine Trade? Quantifying the Output Mix, Factor Price and Skill-Biased Technology Channels”

by

Peter Morrow and Daniel Trefler

Table B1: $(\lambda_{gi}^{R}/\lambda_{g,us}^{R})(\lambda_{Ui}^{V})^{\gamma_{gi}^{V}}$

Industry	AUS	AUT	BEL	BGR	BRA	CAN	CHN	CYP	CZE	DEU	DNK	ESP	EST	FIN	FRA	GBR	GRC	HUN	IDN
AtB	1.18	0.87	0.82	0.29	0.35	1.02	0.21	0.46	0.59	0.96	0.87	0.87	0.43	0.79	1.25	1.03	0.50	0.55	0.10
C	1.25	0.66	0.45	0.24	0.32	1.11	0.27	0.15	0.43	0.53	0.86	0.44	0.23	0.42	0.60	0.98	0.43	0.32	0.07
15t16	1.01	1.15	0.98	0.41	0.50	0.96	0.34	0.11	0.51	1.06	0.89	0.85	0.48	0.88	1.00	1.22	0.68	0.61	0.26
17t18	1.00	0.87	0.78	0.46	0.35	0.79	0.44	0.37	0.49	0.82	0.62	0.81	0.38	0.84	0.96	0.96	0.69	0.51	0.37
19	1.22	0.87	1.06	0.53	0.85	0.84	0.65	0.52	0.31	0.81	0.52	1.18	0.40	1.02	1.88	0.96	0.72	0.64	0.52
20	1.11	1.08	0.93	0.47	0.45	0.88	0.39	0.35	0.68	1.13	1.14	0.77	0.66	0.98	0.92	1.03	0.42	0.68	0.32
21t22	0.88	0.97	0.91	0.25	0.39	1.16	0.35	0.30	0.42	0.97	0.84	0.77	0.39	1.05	0.84	0.93	0.41	0.39	0.23
23	0.57	1.01	1.17	0.47	0.57	0.54	0.59	0.23	0.55	1.23	0.36	0.76	0.80	1.09	1.08	0.65	0.53	1.58	0.26
24	1.05	1.17	0.91	0.36	0.47	0.82	0.59	0.34	0.56	1.27	1.02	0.86	0.33	0.83	0.93	1.03	0.50	0.56	0.20
25	0.70	1.01	0.84	0.26	0.35	0.87	0.40	0.40	0.53	1.18	1.14	0.82	0.40	0.89	1.02	1.19	0.53	0.53	0.28
26	0.69	1.24	1.04	0.38	0.45	0.81	0.54	0.47	0.65	1.14	1.29	1.00	0.45	1.06	1.15	1.12	0.54	0.60	0.18
27t28	0.73	0.92	0.61	0.45	0.53	0.80	0.48	0.30	0.53	1.08	1.03	0.86	0.31	0.71	0.99	1.12	0.47	0.48	0.21
29	0.72	0.94	0.92	0.29	0.36	0.87	0.39	0.21	0.43	1.11	0.88	0.67	0.25	0.74	0.92	1.01	0.44	0.48	0.19
30t33	0.71	0.79	0.81	0.23	0.29	0.62	0.29	0.11	0.18	0.81	0.72	0.44	0.11	0.55	0.72	0.65	0.32	0.18	0.28
34t35	0.76	0.51	0.42	0.16	0.49	0.51	0.46	0.14	0.53	0.90	0.59	0.57	0.31	0.59	0.73	0.88	0.45	0.39	0.21
36t37	0.69	0.90	0.55	0.35	0.33	0.97	0.35	0.32	0.48	0.92	0.79	0.62	0.41	0.68	0.88	0.93	0.42	0.48	0.25
E	1.34	0.41	1.48	0.52	0.21	1.64	0.40	0.20	0.66	1.58	1.23	0.81	0.53	1.27	1.07	0.70	0.48	0.57	0.15
F	0.71	1.23	0.93	0.44	0.29	1.13	0.40	0.47	0.47	1.27	1.09	0.54	0.52	0.70	0.92	0.81	0.50	0.66	0.38
50-52	1.28	1.18	1.50	0.47	0.15	1.39	0.24	0.47	0.72	1.18	0.97	0.82	0.36	0.74	0.87	1.06	0.55	0.57	0.16
H	0.65	0.89	0.57	0.24	0.11	0.83	0.20	0.46	0.35	0.75	0.63	0.50	0.24	0.47	1.08	0.64	0.46	0.37	0.16
60-64	0.83	0.65	0.69	0.25	0.22	0.84	0.27	0.24	0.38	0.61	0.40	0.54	0.27	0.62	0.81	0.74	0.37	0.39	0.20
J,70,71t74	1.00	1.07	1.24	0.17	0.15	1.37	0.29	0.25	0.48	0.95	1.05	0.64	0.24	0.86	1.10	1.06	0.38	0.37	0.15
L-P	0.90	0.96	1.42	0.22	0.18	1.08	0.24	0.24	0.41	0.87	0.96	0.58	0.23	0.66	1.19	0.79	0.36	0.30	0.17

Notes: This table reports the left hand side of equation (30) raised to the power γ_{gi}^{V}. For space, we report NACE industry codes rather than industry names. These map onto verbal descriptions as follows: Agriculture (AtB); Mining (C); Food, Beverages, Tobacco (15t16); Textiles and Textile Products (17t18); Leather and Footwear (19); Wood and Products of Wood (20); Pulp, Paper, Printing, and Publishing (21t22); Coke, Refined Petroleum, and Nuclear Fuel (23); Chemicals (24); Rubber and Plastics (25); Non-Metallic Minerals (26); Basic and Fabricated Metals (27t28); Machinery, nec. (29); Electrical and Optical Equipment (30t33); Transport Equipment (34t35); Manufacturing, nec.(36t37); Electricity, Gas, Water Supply (E); Construction (F); Wholesale and Retail Trade (50,51,52); Hotels and Restaurants (H); Transport (60-64); Finance, Insurance, Real Estate (J,70,71t74); Government Services (L,M,N,O,P). Mappings from country codes to country names are in Appendix C. See Appendix D.1 for details of their calibration.

Table B1 Continued: $(\lambda^R_{gi}/\lambda^R_{g,us})(\lambda^V_{Ui})^{\gamma^V_{gi}}$

Industry	IND	IRL	ITA	JPN	KOR	LTU	LVA	MEX	MLT	NLD	POL	PRT	ROM	RUS	SVK	SVN	SWE	TUR	TWN
AtB	0.04	0.61	1.00	0.74	0.30	0.36	0.39	0.33	0.50	1.00	0.42	0.60	0.31	0.31	0.46	0.55	1.23	0.34	0.43
C	0.02	0.47	0.72	0.35	0.14	0.25	0.24	0.15	0.17	0.77	0.35	0.40	0.27	0.40	0.21	0.53	0.90	0.27	0.14
15t16	0.29	0.96	0.91	0.90	0.40	0.62	0.09	0.54	0.52	0.87	0.57	0.69	0.43	0.36	0.56	0.63	1.15	0.46	0.48
17t18	0.42	0.57	1.02	0.82	0.55	0.40	0.34	0.42	0.54	0.69	0.46	0.73	0.39	0.27	0.39	0.42	0.93	0.49	0.56
19	0.35	0.69	1.28	1.01	0.71	0.85	0.21	0.60	0.38	0.98	0.63	0.93	0.53	0.38	0.33	0.66	0.81	0.62	0.60
20	0.17	0.83	0.94	1.00	0.40	0.67	0.67	0.28	0.35	1.01	0.72	0.66	0.47	0.60	0.66	0.86	1.19	0.55	0.47
21t22	0.18	0.50	0.86	0.83	0.30	0.30	0.24	0.32	0.41	0.84	0.39	0.69	0.30	0.42	0.46	0.48	1.23	0.36	0.35
23	0.67	1.98	0.90	1.38	0.70	1.01	0.12	0.55	0.16	0.64	0.86	0.63	1.07	1.48	1.00	0.72	0.63	0.46	0.74
24	0.27	0.53	0.86	0.83	0.35	0.27	0.19	0.42	0.45	0.72	0.51	0.55	0.51	0.51	0.49	0.61	1.43	0.48	0.31
25	0.33	0.75	1.04	0.91	0.51	0.36	0.35	0.39	0.46	0.59	0.53	0.68	0.36	0.35	0.53	0.71	1.03	0.45	0.45
26	0.22	0.76	1.11	1.16	0.51	0.36	0.42	0.36	0.48	0.97	0.59	0.91	0.46	0.35	0.50	0.77	1.09	0.47	0.58
27t28	0.31	0.76	0.98	0.78	0.34	0.31	0.38	0.40	0.40	0.96	0.52	0.52	0.50	0.53	0.53	0.51	1.04	0.42	0.40
29	0.22	0.57	0.97	1.01	0.42	0.26	0.32	0.30	0.18	0.80	0.47	0.58	0.42	0.42	0.38	0.48	1.04	0.39	0.38
30t33	0.20	0.31	0.91	0.82	0.27	0.25	0.24	0.22	0.10	0.51	0.33	0.35	0.32	0.31	0.27	0.42	0.72	0.31	0.29
34t35	0.33	0.60	0.80	0.71	0.48	0.28	0.27	0.52	0.21	0.62	0.42	0.47	0.50	0.28	0.25	0.35	0.82	0.39	0.50
36t37	0.26	0.29	0.83	0.76	0.50	0.41	0.34	0.51	0.45	1.08	0.51	0.63	0.38	0.28	0.47	0.60	0.85	0.34	0.07
E	0.15	0.76	1.03	1.41	0.39	0.58	0.50	0.43	0.81	0.71	0.57	0.45	0.39	0.65	0.49	0.68	1.85	0.34	0.36
F	0.19	0.76	1.06	0.50	0.52	0.42	0.55	0.31	0.55	0.97	0.52	0.54	0.37	0.37	0.46	0.60	1.36	0.37	0.46
50-52	0.01	0.70	1.15	1.03	0.28	0.27	0.39	0.32	0.43	1.43	0.48	0.81	0.35	0.41	0.53	0.61	1.34	0.26	0.32
H	0.11	0.44	0.50	0.91	0.29	0.16	0.29	0.17	0.37	0.70	0.25	0.50	0.35	0.31	0.28	0.34	0.66	0.25	0.33
60-64	0.14	0.45	0.79	0.84	0.31	0.25	0.30	0.30	0.47	0.74	0.33	0.48	0.29	0.38	0.30	0.41	0.55	0.22	0.38
J,70,71t74	0.03	0.43	1.27	0.86	0.22	0.20	0.32	0.22	0.45	0.91	0.34	0.58	0.41	0.32	0.39	0.47	1.27	0.21	0.29
L-P	0.02	0.47	1.02	0.78	0.17	0.16	0.22	0.15	0.47	0.89	0.24	0.51	0.35	0.27	0.31	0.38	1.16	0.20	0.29

Notes: This table reports the left hand side of equation (30) raised to the power γ^V_{gi}. For space, we report NACE industry codes rather than industry names. These map onto verbal descriptions as follows: Agriculture (AtB); Mining (C); Food, Beverages, Tobacco (15t16); Textiles and Textile Products (17t18); Leather and Footwear (19); Wood and Products of Wood (20); Pulp, Paper, Printing, and Publishing (21t22); Coke, Refined Petroleum, and Nuclear Fuel (23); Chemicals (24); Rubber and Plastics (25); Non-Metallic Minerals (26); Basic and Fabricated Metals (27t28); Machinery, nec. (29); Electrical and Optical Equipment (30t33); Transport Equipment (34t35); Manufacturing, nec.(36t37); Electricity, Gas, Water Supply (E); Construction (F); Wholesale and Retail Trade (50,51,52); Hotels and Restaurants (H); Transport (60-64); Finance, Insurance, Real Estate (J,70,71t74); Government Services (L,M,N,O,P). Mappings from country codes to country names are in Appendix C. See Appendix D.1 for details of their calibration.