Global Value Chains and Inequality with Endogenous Labor Supply*

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Abstract

We assess the role of global value chains transmitting global integration shocks to aggregate trade as well as distributional outcomes. We develop a multi-country general equilibrium trade model that features multi-stage production, with different stages having different productivities and using factors (occupations) with different intensities. The model also features a Roy mechanism, in which heterogeneous workers endogenously choose their sector and occupation. Country- and worker-level comparative advantages interact. A reduction in trade costs leads to countries specializing in their comparative advantage sectors and production stages. This specialization changes labor demand and also leads to more workers shifting to the comparative advantage sectors and occupations. We show that the intensity of the global value chain magnifies the aggregate effects of trade liberalization, but it has a non-monotonic effect on the skill premia. Our counterfactuals show that China's integration into world economy increases the skill premium in both US and China, but sectoral variation in GVC intensity limits the size of distributional impacts.

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1 Introduction

One of the most significant economic developments over the past half-century is the increased fragmentation of production across borders. Goods are produced in sequential stages that traverse multiple countries – a global value chain. Countries specialize in particular stages of a good's production process. This increase in vertical specialization has occurred under a backdrop of a broad increase in international trade, one of the defining features of globalization across the world during this period.

Partly because of this backdrop, most of the research examining the effects of global integration on wages, employment, and other variables has focused on total trade. Autor et al. (2013) is a recent example. This has also been exemplified in the factor content studies that trade and labor economists have conducted since the 1990s. The purpose of our paper is to assess the role of global value chains as a propagation mechanism transmitting global integration shocks, such as China joining the WTO, to aggregate trade outcomes, as well as distributional outcomes, such as the skill premia.

Our approach is to build a model of global value chains and international trade and then to calibrate it and use it to study global integration shocks. We introduce global value chains following the work of Antràs and de Gortari (2017) and de Gortari (2017). They develop a tractable framework for incorporating multi-stage production in an international trade model that generalizes and extends previous research on this subject. In addition, a key feature of our model is to include for multiple sectors, multiple factors, and a labor supply channel. In particular, following Lee (2017), we include Roy selection effects, in which heterogeneous workers choose occupations and sectors based on their individual productivities in these occupations and sectors, as well as on prevailing prices. Lee (2017) and others have shown that these channels enhance our understanding of how trade affects inequality and are quantitatively important in explaining the increase in inequality.

The core elements of our model revolve around the production of a final good and the worker's decision of sector and occupation. A final good is made in a sequence of stages. Each stage involves labor, a composite intermediate, and output from the previous stage. There are several labor inputs, which we call "occupations". Different stages use these occupations with different intensities. The presence of the composite intermediate and the previous stage's output helps generate both "roundabout" and "snake" features in production. The final goods have two uses, consumption and input into the composite intermediate. On the worker's side, each worker is of an exogenous type. Within each type, a worker draws occupation and sector specific productivities. Based on these productivities, as well as on prevailing prices, workers choose their optimal sector and occupation. Our individual goods and workers are embedded in a multi-country general equilibrium framework. This framework features both country- and worker-level comparative advantages.

For our analysis, we first introduce a general version of the model and then study a simplified version of the model in order to develop intuition. We study a "2^5" version of the model in terms of countries, worker types, sectors, stages, and occupations. We examine the response of GVCs, skill premia, and other variables to lower trade costs. The lower trade costs are mediated through several demand and supply forces before ultimately affecting GVCs and skill premia. The lower trade costs facilitate specialization in particular sectors and production stages. In turn, this changing specialization pattern shifts the relative demand for occupations based on stage-specific occupation intensities. This affects the equilibrium wage, which then affects workers' choices of occupations and sectors. Ultimately, the skill premia are affected.

The intensity of a GVC is captured by the importance of the first-stage output used as an input in second stage production. The greater the importance of the first-stage output, the higher the GVC intensity in the 2-stage version of our model. We also look at sectoral variation in the GVC intensity. Our numerical exercises show that GVC intensity has a non-monotonic effect on the skill premia response to a decline in trade costs. Also, we show that the sectoral variation in the GVC intensity plays an important role in transmitting trade shocks to labor markets through GVCs. Direction and magnitude of changes in the skill premium from trade liberalization depends on the occupation intensity of each production stage and on the GVC intensity of each sector. Country-level comparative advantage determines sector- and stage-wise specialization of countries. This specialization will change demands for occupations depending on the occupation intensity in each production stage. In addition, how much each sector depends on each production stage will put different weights on the shift of occupation-level labor demand, because this shift depends on actual value that each stage adds to the entire value chain. A simulation of a simple version of our model shows this core mechanism.

We then calibrate a general version of our model for three countries, China, USA, and constructed rest of the world, five worker types, four sectors, two stages, and five occupations. Some of our parameters draw directly from the data, others are assigned, and the others – including the worker productivity parameters, and the production function parameters (productivities of sector and stage, occupational intensity coefficients, value-added share, and GVC intensity parameters) – are calibrated to match moments in the data. Our calibrated model reveals several patterns. First, based on relative endowments and productivities, China has a comparative advantage in the manufacturing sector and the downstream production stage, and the US has a comparative advantage in services and the upstream production stage. Second, production stages have different occupation intensities across countries. For example, the downstream production stage is relatively high-skilled-occupation-intensive in China, but low-skilled-occupation-intensive in the US. Third, sectors significantly differ in GVC intensity. Upstream production stages have relatively larger value-added in the manufacturing sector than in the service sector. Lastly, workers have a clear comparative advantage both across sectors and occupations.

We use our calibrated model to perform counterfactual exercises quantifying aggregate and distributional impacts of the China shock. We study a 50 percent decline in China's trade costs with its trading partners. When trade costs with China go down, all countries specialize further in their comparative advantage stages and sectors. The degree of stage-wise specialization is larger in sectors with a larger GVC intensity, e.g., manufacturing. The greater the GVC intensity, the larger the magnification of aggregate effects such as trade. This is consistent with previous research.

In addition, we find that skill premium rises in all three countries. In the US and China, the lower trade costs induce specialization to shift towards sectors and stages that use high-skilled-occupations more intensively. As indicated above, for China that involves manufacturing and the downstream stage, and for the US, that involves the service sector and the upstream stage. In addition, the worker-level productivity estimates imply that better educated workers are better off in the high-skilled occupations. Hence, our rich framework is able to reproduce the stylized fact that trade liberalizations are often associated with skill premia increases in both skill-abundant and non-skill-abundant countries.

On the other hand, we do not find that GVCs magnify the skill premia effect. Overall, the increase in skill premia is limited in magnitude, around 1% or less. This is because, according to our calibrated parameters, each country specializes in sectors and stages that do not have a large share of value-added in the entire production chain. Hence, while there are large changes in specialization owing to the lower trade costs, these large changes do not translate into large skill premia effects.

1.1 Related Literature

Our research is connected to several strands of research. One strand is the trade and wages research that sought to examine the effects of increased U.S. imports from developing countries on the skill premia. This research was especially active in the mid-1990s, and includes Katz and Murphy (1992), Lawrence and Slaughter (1993), Krugman (1995), and Feenstra and Hanson (1999) among others. All of these papers essentially employed a Heckscher-Ohlin type (HO) framework with its Stolper-Samuelson and factor content of trade implications. The main findings tended to be that the effect of trade was not large. However, the survey article by Goldberg and Pavcnik (2007) showed that the predictions of a simple Heckscher-Ohlin (HO) framework do not hold up in the data. In particular, skill premia tended to rise in both developed and developing countries following trade liberalizations. Krugman (2008) revisits the trade and wage issues from the mid-1990s with the benefit of 15 years of additional data. In addition, Krugman argues that increased vertical specialization can generate inequality via Stolper-Samuelson effects. To our knowledge, Krugman's paper is the only paper that makes a case for examining the consequences of vertical specialization for inequality.

In recent years, there has been a new wave of interest on the employment and wage effects of increased trade. This is not surprising, because the emergence of China as a significant global economic force has only come about in the past 10-15 years. Autor et al. (2013), Pierce and Schott (2016), and many other papers in the literature document significant effects of China on labor markets of major partner countries such as the U.S. With the new interest has come an expanded set of methodologies. One new approach involves applying models with numbers, i.e., quantitative theory. Burstein and Vogel (2016) combine an HO framework in a model that features heterogeneous firms and skill-biased productivity. Our framework is in this vein.

Our paper is also related to a literature about offshoring and skill upgrading. Feenstra and Hanson (1995), Costinot and Vogel (2010), and Zhu and Trefler (2005) discuss how offshoring may increase the skill premium in both North and South by making both countries specialize in high-skill-intensive sectors. These papers do not explicitly model a vertical production structure. Our model looks at this argument through the lens of GVCs, because offshoring involves vertical specialization across production stages by nature.

A second strand of research is on documenting the extent of global value chains, vertical specialization, value-added exports, and related concepts, as well as on building models of these concepts. Contributions on the documentation side include Hummels et al. (2001), Johnson and Noguera (2012); Antràs and Chor (2013), and Koopman et al. (2014). Contributions on the modeling side include Yi (2003; 2010), Johnson and Moxnes (2016), and most recently, Antràs and de Gortari (2017) and de Gortari (2017). The latter two papers develop a general framework for GVCs and show how to map special cases of this framework into the Eaton and Kortum (2002) framework. Our modeling of GVCs draws from Antràs and de Gortari (2017); it combines that paper with Lee (2017).

To investigate the link between trade and labor market outcomes, such as wage inequality and labor reallocation, increasingly, papers focus on heterogeneous workers. While traditional trade models such as the HO model and the specific factors model assume that workers are all homogeneous in their productivities conditional on observable characteristics, this assumption misses the fact that workers differ in their productivities in reality. This worker-level heterogeneity is important especially when we study the effect of trade on labor market outcomes, because workers with same observable characteristics may respond to trade shocks differently depending on their idiosyncratic productivities. In recent years, trade models bring the idea of the Roy (1951) model to introduce worker heterogeneity under the setting of assignment models: e.g., Teulings (2005), Ohnsorge and Trefler (2007), and Costinot and Vogel (2010; 2015). Worker heterogeneity is introduced to trade models also based on a search and matching framework: e.g., Grossman et al. (2015), Helpman and Itskhoki (2010), and Helpman et al. (2016).

Our paper is also closely related to a recent strand of literature on quantitative models with the Roy-based assignment structure. One of the key assumptions in this literature is that workers' idiosyncratic productivity is randomly drawn from a type-II extreme value distribution, a Fréchet distribution. Hsieh et al. (2013), Burstein et al. (2015), Lagakos and Waugh (2013), Galle et al. (2017), and Lee (2017) use this assumption to investigate the role of worker heterogeneity in disentangling labor market outcomes in one country from labor demand shocks such as technological change or trade liberalization. Our paper also relies on this distributional assumption when we characterize workers' heterogeneous productivities. We introduce this Roy-based assignment framework into a multi-stage GVC model, where each stage of production is formulated based on the EK model. We can thus investigate the general equilibrium relation between workers' endogenous labor supply and trade through GVC in our model. To numerically solve our multi-country GVC model for a general equilibrium, we base our work on the iterative algorithm provided by Alvarez and Lucas (2007).

More papers in the literature recently focus on the occupational dimension as an important channel through which trade shocks are disseminated across workers--e.g., Autor et al. (2015), Ebenstein et al. (2014), Traiberman (2016), Harrigan et al. (2016). Our framework also allows workers to endogenously choose occupations in response to trade shocks under the GVC setting. We show that worker heterogeneity plays also a significant role for occupation-level labor reallocation. With this occupation-level analysis, we can also analyze the effect of generic trade shocks or GVC shocks on job polarization which is well-documented in the data for many developed economies.

The core mechanism of our model can be further connected to the literature on trade, inequality, and a declining labor share around the world. A recent paper by Dao et al. (2017) provides suggestive evidence about the effect of increased participation in GVCs on declining labor shares in both developed and developing countries. Countries specialize in their capital-intensive and high-skilled-task-intensive stages as they participate in GVCs more. Although we do not explicitly consider capital in our model, the stage-wise specialization pattern and stage-specific occupation intensities that we quantify in this paper can be linked to explain declining labor shares with capital-skill complementarity as in Grossman et al. (2017).

The next section lays out our baseline model. This is followed by a description of a simpler version of our model with just two stages of production, two countries, two occupations, and two labor types. We solve the simpler version of the model and conduct several numerical exercises to illustrate how the model works. Section 4 describes our calibration, and section 5 discusses our couterfactual exercises with the model.

2 Model

In this section, we describe our model. Because the model has many features, we provide an overview first. Our model draws from the general global value chain (GVC, hereafter) model developed by Antràs and de Gortari (2017). We extend their framework by adding three features: multiple factors of production, multiple sectors, and heterogeneous workers. All three features are essential to investigate the role of GVCs in the effect of increased trade on inequality.

In our model, each sector is comprised of a continuum of final goods. Each final good is produced through a specific global value chain encompassing multiple stages of production that can potentially cross multiple countries. Each stage of production is produced with value-added and with intermediate inputs. Value-added consists of multiple factors of production, called occupations. There are two categories of intermediate inputs. One category is a composite aggregate good. The second category of intermediates is good and stage-specific: the previous stage's output. The inclusion of the previous stage's output is the key GVC component.

Countries have comparative advantages both across sectors and stages. To distinguish these two types of comparative advantages, we assume that the primary source of each comparative advantage is different. Sector-wise comparative advantage is primarily from difference in Ricardian productivities as in Eaton and Kortum (2002). On the other hand, stage-wise comparative advantage arises mainly from the standard *Heckscher-Ohlin (HO)* *channel*, as we assume that different stages of production have different factor intensities and that countries have different factor endowments.

In addition, workers are heterogeneous in their sector and occupation-specific productivities. Workers endogenously choose their occupation and sector based on their productivities: the *Roy channel*. Introducing the Roy framework into a general equilibrium trade model is based on Lee (2017). Our model will deliver interaction between the Ricardian and HO channels, the Roy channel, and GVCs.

2.1 Preferences, Technologies, and Workers

Our model features N countries, S sectors, value chains of fixed length J, O occupations, and T worker types. Each country is distinguished by its production technologies, endowment of worker types, and the productivity of workers within and across types. Within each sector s, $s = 1, \ldots, S$, there is a continuum of final goods over a set Ω^s of mass 1. Each final good $\omega \in [0, 1]$ is produced following a specific value chain of length J. The optimal value chain for a final good ω consumed in country n is a J-dimensional vector of countries where each stage j of production takes place. In other words, intermediate stages of a product can cross multiple borders along the value chain. For each stage, the production factors are occupations (managers, clerical staff, etc.) o, $o = 1, \ldots, O$. Occupation intensities vary across stages of production and countries. As mentioned above, the production technology also consists of two categories of intermediates, an aggregate composite intermediate, and a good and stage-specific intermediate.

Each country i, $i = 1, \ldots, N$, is exogenously endowed with $\bar{L}_{i,t}$ workers of type t, $t = 1, \ldots, T$. In our quantitative analysis these types will be associated with observable worker characteristics, such as education. Each worker of each type "draws" a sector and occupation specific productivity, and on the basis of that productivity and prevailing occupation-sector-specific wages, chooses to work in the occupation and sector that delivers the highest return.

Preferences Consumers have common nested CES preference over final goods

$$U_i = \prod_{s=1}^{S} (C_i^s)^{b^s},$$

$$\text{where } C_i^s \equiv \left(\int_{\Omega^s} (C_i^{s,F}(\omega))^{(\sigma-1)/\sigma} d\omega\right)^{\sigma/(\sigma-1)}$$

where $C_i^{s,F}(\omega)$ is consumption of a final good ω of sector s in country i. The expenditure share of each sector is given by b^s with $\sum_s b^s = 1$. $\sigma > 0$ is the elasticity of substitution between goods within the sector.

Production Technology As outlined above, each final good ω is produced from a specific value chain of length J during production, and this value chain is potentially spread over multiple countries. We denote the sequence of producing countries for a product ω by $l(\omega) = (l^1(\omega), \ldots, l^J(\omega))$. At each stage j of the value chain for a product ω, firms use domestic labor, the stage $j-1$ good for ω, and a composite intermediate. The use of the immediately preceding stage captures the "snake" structure of production (as in Yi (2003)) and is the key feature of the value chain. The composite intermediate is a CES aggregate of the final goods, and it captures the "roundabout" structure of production, as in Caliendo and Parro (2015). The share of composite intermediates in production varies by country and sector.

Countries possess technologies for any intermediate stage of production from $j = 1$ to $j = J-1$, and also for final assembly of stage J, for all goods in all sectors. The production function in country i for stage j of good ω in sector s is Cobb-Douglas:

$$f_i^{s,j}(x_i^{s,j}, L_i^{s,j,1}(\omega), \ldots, L_i^{s,j,O}(\omega), m_i^{s,j-1}(\omega))$$

$$= z_i^{s,j}(\omega)((x_i^{s,j})^{1-\alpha_i^s} \prod_o (L_i^{s,j,o}(\omega))^{\beta_i^{j,o}\alpha_i^s})^{\gamma^{s,j}} (m_i^{s,j-1}(\omega))^{1-\gamma^{s,j}},$$

Focusing first on the intermediate and value-added inputs into production, $x_i^{s,j}$ is the composite intermediate good, which, as noted before, is a CES aggregate of the final goods used by stage j producers of sector s in country i; $L_i^{s,j,o}(\omega)$ is the occupational input from each of O occupations; and $m_i^{s,j-1}(\omega)$ is the stage $j-1$ good for ω of sector s.

The three key parameters governing the importance of each of these inputs are $\beta_i^{j,o}$, $\gamma^{s,j}$, and α_i^s. All three parameters range from 0 to 1. $\beta_i^{j,o}$ captures the importance of each occupational input o. This parameter varies across occupations, stages, and countries. For each stage j and country i, $\sum_o \beta_i^{j,o} = 1$. $1 - \gamma^{s,j}$ captures the importance of the $j-1$ stage input in stage j. This parameter varies across stages and sectors. A lower value of $\gamma^{s,j}$ corresponds to a greater importance of the snake structure, and a lower importance of the composite intermediate and value-added taken together.[1] More formally, as $\gamma^j \to 0$, the snake or value chain term dominates the roundabout and value-added terms, and vice versa for $\gamma^j \to 1$. α_i^s captures the relative importance of value-added and the composite intermediate with higher values of α_i^s corresponding to greater importance of

[1]Note that these two terms constitute the "typical" Eaton and Kortum (EK) strucure of production; hence, $\gamma^{s,j}$ can also be thought of as capturing the importance of the EK structure.

value-added. This parameter varies across sectors and countries. We will call this parameter as value-added share. Finally, we assume that the initial stage 1 is produced using only occupations and composite intermediates; in other words, we assume $\gamma^{s,1} \equiv 1$ for every $s = 1, \ldots, S$.

To summarize, for each stage of production, the importance of the previous stage, i.e., of the value chain, is captured only by $1 - \gamma^{s,j}$, the importance of the composite intermediate, i.e., the roundabout term, is captured by $(1 - \alpha_i^s)\gamma^{s,j}$, and the importance of the occupations, taken together, i.e., value-added, is captured by $\alpha_i^s \gamma^{s,j}$.

Factor-neutral productivity for stage j of sector-s product ω in country i is denoted by $z_i^{s,j}(\omega)$. We assume the productivity follows a Fréchet distribution from Eaton and Kortum (hereafter, EK, 2002). Productivity $z_i^{s,j}(\omega)$ is randomly drawn from

$$F_i^{s,j}(z) = \exp(-A_i^s z^{-\nu\tilde{\gamma}^{s,j}}),$$

where $\tilde{\gamma}^{s,j} \equiv \prod_{j'=j+1}^{N}(1 - \gamma^{s,j'}) \in [0, 1]$. We further assume that productivity draws are independent across sectors and stages. A_i^s governs the scale of productivity for sector s in country i. We assume that this scale parameter does not vary by stage. $\nu\tilde{\gamma}^{s,j}$ captures the dispersion of stage j productivities. ν is the standard Fréchet shape parameter, and governs the common variance of stage j productivity. The effective variance of stage j is stage-specific and is based on $\tilde{\gamma}^{s,j}$.

The stage-specific shape parameter $\nu\tilde{\gamma}^{s,j}$ has two advantages. First, as argued in Antràs and de Gortari (2017), this probability distribution makes a sequential sourcing decision equivalent to the case where a lead firm chooses the entire sourcing path from the beginning. This feature provides great analytic tractability, which we will discuss in more detail in the next subsection. Second, we can conveniently characterize the magnification effect of GVC as discussed in Yi (2003). At the equilibrium, the effective trade elasticity $\nu\tilde{\gamma}^{s,j}$ is larger in downstream production stages, as $\tilde{\gamma}^{s,j}$ is monotonically increasing in j for every s. The magnification effect of GVC is thus active through $\tilde{\gamma}^{s,j}$ and potentially different across sectors. (In addition, $\sum_j \gamma^{s,j}\tilde{\gamma}^{s,j} = 1$ for every s by the definition of $\tilde{\gamma}^{s,j}$, and we assume $\tilde{\gamma}^{s,J} \equiv 1$ for every s.)

Our rich structure provides Ricardian and HO motives for trade. The Ricardian channel is captured by $z_i^{s,j}(\omega)$, and is present across stages and sectors. The HO channel operates through $\beta_i^{j,o}$. Different stages use occupations with different intensities. For example, a design stage would use more designers or engineers, while an assembly stage would employ relatively more production workers. Note that the value-added by a particular occupation depends on the stage, not on the sector. However, the effective occupation intensity $\beta_i^{j,o}\alpha_i^s\gamma^{s,j}$ depends also on sectors.

Workers Workers are heterogeneous in their productivities for each sector and occupation pair (s, o). A characterization of worker heterogeneity is based on Lee (2017). Each worker supplies one unit of time. Workers vary in their efficiency units of that time. The number of efficiency units $\epsilon^{s,o}$ that each individual worker of type t can supply for a specific (s, o) is randomly drawn from the following Fréchet distribution:

$$G_t^{s,o}(\epsilon) = \exp(-T_t^{s,o}\epsilon^{-\theta_t}).$$

We assume that these distributions do not vary by country. Worker heterogeneity characterized by $G_t^{s,o}(\epsilon)$ in this model is related to fundamental complementarity between workers' skills and sector- and occupation-specific tasks, which is not necessarily different across countries.

Two types of stochastic comparative advantage arise from this probabilistic assumption. First, between-worker-type comparative advantage is governed by the relative magnitude of parameters $T_t^{s,o}$. For example, if $\frac{T_t^{s,o}}{T_t^{s',o'}} > \frac{T_{t'}^{s,o}}{T_{t'}^{s',o'}}$ holds, then it is more likely that a type t worker has comparative advantage for sector s and occupation o compared to another worker of type t' and for another pair (s', o'). Second, within-worker-type comparative advantage depends on the shape parameter θ_t. If workers' productivities are more dispersed within a type–i.e., lower θ_t–, then effects from the within-worker-type comparative advantage will be stronger than in the case of a larger θ_t. We further assume that draws of idiosyncratic productivity for each (s, o) are independent, which gives us the following joint distribution for a vector of worker productivity $\epsilon = (\epsilon^{1,1}, \ldots, \epsilon^{s,o}, \ldots, \epsilon^{S,O})$:

$$G_t(\epsilon) = \exp(-\sum_{s',o'} T_t^{s',o'}\epsilon^{-\theta_t}).$$

This framework for the labor supply side is an important channel which has not been widely studied in the literature. While changes in trade costs operate as one of labor demand shocks along the GVC, workers potentially respond to these shocks differently based on their own comparative advantage. This Roy channel allows for a more general sorting pattern of workers. Instead of assuming an exact one-to-one relationship between workers skills and occupations, we allow for endogenous matching between skills, sectors, and occupations.

2.2 Equilibrium Sourcing Decision

In the above model, a final producer for ω chooses the entire path of $l(\omega) = (l^1(\omega), \ldots, l^J(\omega))$ by minimizing the total cost of production across all J stages. However, this approach makes solving the model challenging, because we can no longer take advantage of the convenient characteristics of the Fréchet distribution. To deal with this issue, Antràs and de Gortari (hereafter, AG, 2017) introduce two alternative approaches. The first is a "sequential" approach in which each stage j producer chooses an optimal source for the $j-1$ stage by minimizing only its stage-specific production cost. The key assumption that they introduce is that stage j producers know the **exact productivity draw of the stage** $j-1$ **producers**, but do not know that of stage $1, \ldots, j-2$ producers. Instead, stage j producers know **only the productivity distribution of upstream producers up to stage** $j-2$; thus, they take the expectation of productivity up to stage $j-2$ as given when they minimize the production cost for stage j. Thus, this is a limited information approach. The second approach is a "lead-firm" approach in which the assumption of a country-stage-specific Fréchet productivity parameter is replaced by a single Fréchet productivity parameter for an entire GVC. So, in a world with N countries and J stages, there are N^J possible GVCs, each with its own Fréchet productivity parameter. AG show that these two approaches are equivalent at the equilibrium under the probabilistic assumption of $z_i^j(\omega)$ as previously described. Our model draws from their result and, hereafter, we apply the sequential approach.

Another key assumption for the sourcing problem of this model is that each stage's sourcing decision is independent. Combining this assumption and the assumption of limited information on upstream productivities, we can derive an analytical solution for the equilibrium GVC probability. We assume perfect competition for final goods and intermediate inputs, so each country sources from the lowest-cost supplier around the world. Given per-unit wages $w_i^{s,o}$ for each country, sector, and occupation, and a CES price index for final goods P_i, the unit cost for the input bundle excluding materials from the previous stage is given by $c_i^{s,j} \equiv \varphi_i^{s,j}(P_i)^{1-\alpha_i^s} \prod_o (w_i^{s,o})^{\alpha_i^s \beta_i^{j,o}}$, where $\varphi_i^{s,j} \equiv (1-\alpha_i^s)^{-(1-\alpha_i^s)} \prod_o (\alpha_i^s \beta_i^{j,o})^{-\alpha_i^s \beta_i^{j,o}}$ is a Cobb-Douglas constant.

Whenever stage j materials in country i are shipped to another country n to be used in stage $j+1$ production, there is iceberg trade cost $\tau_{in}^s \geq 1$. Trade costs vary by sector. We adopt standard assumptions for iceberg trade costs: $\tau_{ii}^s = 1$ and $\tau_{in}^s \geq \tau_{ik}^s \tau_{kn}^s$ for every s,i,n, and k. Given these assumptions, stage 2 producers of sector s in country i choose the optimal source $l_i^{s,1}(\omega)$ for stage 1 materials of product ω by solving the following problem:

$$l_i^{s,1}(\omega) = \arg\min_l [(p_l^{s,1}(\omega)\tau_{li}^s)^{1-\gamma^{s,2}}] = \arg\min_l [(\frac{c_l^{s,1}}{z_l^{s,1}(\omega)}\tau_{li}^s)^{1-\gamma^{s,2}}],$$

where $c_i^{s,1} = \varphi_i^{s,1}(P_i)^{1-\alpha_i^s}\prod_o (w_i^{s,o})^{\alpha_i^s \beta_i^{1,o}}$.

Before we derive the sourcing decision for stage $j+1$ producers, we define the following expectation variable as introduced by AG using the law of iterated expectations:

$$\begin{aligned}
\Theta_i^{s,j}(x) &\equiv E_j[(p^{s,j}_{l_i^{s,j}(\omega)}(\omega)\tau^s_{l_i^{s,j}(\omega)i})^x] \\
&= E_j[(\frac{(c^{s,j}_{l_i^{s,j}(\omega)})^{\gamma^{s,j}}}{z^{s,j}_{l_i^{s,j}(\omega)}(\omega)})^x \times \Theta^{s,j-1}_{l_i^{s,j}(\omega)}(x(1-\gamma^{s,j})) \times (\tau^s_{l_i^{s,j}(\omega)i})^x].
\end{aligned}$$

We denote the optimal source for stage j materials of sector-s product ω for stage $j+1$ producers of sector s in country i by $l_i^{s,j}(\omega)$. Then, this expectation variable $\Theta_i^{s,j}(x)$ describes the expected price of stage j materials of sector-s product ω to the power of some constant x, if they are shipped from the optimal source country $l_i^{s,j}(\omega)$ to country i. The sourcing decision for stage $j+1$ producers in country i can be written using this expectation variable.

$$l_i^{s,j}(\omega) = \arg\min_l \{(\frac{(c_l^{s,j})^{\gamma^{s,j}}}{z_l^{s,j}(\omega)})^{1-\gamma^{s,j+1}} \times \Theta_l^{s,j-1}((1-\gamma^{s,j+1})(1-\gamma^{s,j})) \times (\tau_{li}^s)^{1-\gamma^{s,j+1}}\}$$

Similarly, final good consumers in country i buy ω from $l_i^{s,J}(\omega)$ which solves

$$l_i^{s,J}(\omega) = \arg\min_l \{\frac{(c_l^{s,J})^{\gamma^{s,J}}}{z_l^{s,J}(\omega)} \times \Theta_l^{s,J-1}(1-\gamma^{s,J}) \times \tau_{li}^s\}$$

Probability of GVC The probability that stage $j+1$ producers of sector s in country i source stage j materials from another country n is

$$\begin{aligned}
\Pr(l_i^{s,j}(\omega) = n) &= \Pr[(\frac{(c_n^{s,j})^{\gamma^{s,j}}}{z_n^{s,j}(\omega)})^{1-\gamma^{s,j+1}} \times \Theta_n^{s,j-1}((1-\gamma^{s,j+1})(1-\gamma^{s,j})) \times (\tau_{ni}^s)^{1-\gamma^{s,j+1}} \\
&\leq \min_{n'}(\frac{(c_{n'}^{s,j})^{\gamma^{s,j}}}{z_{n'}^{s,j}(\omega)})^{1-\gamma^{s,j+1}} \times \Theta_{n'}^{s,j-1}((1-\gamma^{s,j+1})(1-\gamma^{s,j})) \times (\tau_{n'i}^s)^{1-\gamma^{s,j+1}}].
\end{aligned}$$

For notational simplicity, we define $B_{ni}^{s,j} \equiv (c_n^{s,j})^{\gamma^{s,j}(1-\gamma^{s,j+1})} \times \Theta_n^{s,j-1}((1-\gamma^{s,j+1})(1-\gamma^{s,j})) \times (\tau_{ni}^s)^{1-\gamma^{s,j+1}}$ for each s and $j = 1, \ldots, J-1$, and $B_{ni}^{s,J} \equiv (c_n^{s,J})^{\gamma^{s,J}} \times \Theta_n^{s,J-1}(1-\gamma^{s,J}) \times \tau_{ni}^s$. Using the Fréchet distribution of product-specific productivity for each stage and each country, the equilibrium probability of the sourcing decision by stage $j+1$ producers of sector s in country i can be written as

$$\Pr(l_i^{s,j}(\omega) = n) \quad = \quad \frac{A_n^{s,j}(B_{ni}^{s,j})^{-\nu\tilde{\gamma}^{s,j}/(1-\gamma^{s,j+1})}}{\sum_{n'} A_{n'}^{s,j}(B_{n'i}^{s,j})^{-\nu\tilde{\gamma}^{s,j}/(1-\gamma^{s,j+1})}}$$

for $j = 1, \ldots, J-1$. Similar to the EK model, this probability is equal to the share of stage j goods of sector s that are produced in country n and used for stage $j+1$ production in country i.

This GVC probability clearly shows the magnification effect of hierarchical production as we go downstream. Because $\tilde{\gamma}^{s,j}$ is increasing in j for a given sector s, the effective elasticity of bilateral trade flows $\nu\tilde{\gamma}^{s,j}$ is increasing in j. Therefore, the effect of changes in trade costs between two countries is magnified in downstream production compared to upstream production. As different production stages use occupations with different intensities, the demand for occupations will depend on this magnification effect. The size of the magnification effect varies by sector, as different sectors differ in the GVC intensity based on $\gamma^{s,j}$.

Using the GVC probability result and the independence assumption for sourcing decisions, we derive the equilibrium probability of an entire GVC path. The probability that a final good ω of sector s consumed in country i has followed a specific GVC path $l = (l^1, \ldots, l^J)$ is

$$\begin{aligned}
\lambda_{l,i}^s \quad &= \quad \Pr(l_i^{s,J}(\omega) = l^J | l_{l^J}^{s,J-1}(\omega) = l^{J-1}) \times \Pr(l_{l^J}^{s,J-1}(\omega) = l^{J-1} | l_{l^{J-1}}^{s,J-2}(\omega) = l^{J-2}) \times \ldots \\
&\qquad \ldots \times \Pr(l_{l^2}^{s,1}(\omega) = l^1) \\
&= \quad \frac{\prod_{j=1}^J A_{l^j}^{s,j}[(c_{l^j}^{s,j})^{\gamma^{s,j}}(\tau_{l^j l^{j+1}}^s)]^{-\nu\tilde{\gamma}^{s,j}}}{\sum_{l' \in \mathbf{N}^J} \prod_{j=1}^J A_{l'^j}^{s,j}[(c_{l'^j}^{s,j})^{\gamma^{s,j}}(\tau_{l'^j l'^{j+1}}^s)]^{-\nu\tilde{\gamma}^{s,j}}},
\end{aligned}$$

where $\mathbf{N}^J$ is the set of all possible sequences of N countries along J stages, and $l^{J+1} = i$ and $l'^{J+1} = i$ for all $l' \neq l \in \mathbf{N}^J$. The derivation of this probability again uses the law of iterated expectation and characteristics of the Fréchet distribution.

The expression for bilateral trade flows of final goods of sector s from the location of final assembly n to country i is derived similarly:

$$\Pr(l_i^{s,J}(\omega) = n) \quad = \quad \frac{A_n^{s,J}(B_{ni}^{s,J})^{-\nu}}{\sum_{n'} A_{n'}^{s,J}(B_{n'i}^{s,J})^{-\nu}}.$$

The exact price index of final goods is also derived in a similar way to EK:

$$P_i = \prod_{s=1}^{S}(\frac{P_i^s}{b^s})^{b^s},$$

$$\text{where } P_i^s = [\Gamma(\frac{\nu+1-\sigma}{\nu})]^{1/(1-\sigma)}(\sum_{l' \in \mathbf{N}^J}\prod_{j=1}^{J} A_{l'j}^{s,j}[(c_{l'j}^{s,j})^{\gamma^{s,j}}(\tau_{l'^j l'^{j+1}}^{s})]^{-\nu\tilde{\gamma}^{s,j}})^{-1/\nu}. \tag{1}$$

Again, in this price index, $l^{J+1} = i$ and also $l'^{J+1} = i$ for all $l' \neq l \in \mathbf{N}^J$. We assume $\sigma < \nu + 1$ so that the gamma function in the price index is well-defined.

2.3 Equilibrium Labor Supply

Workers' labor supply response à la Roy model is based on Lee (2017). We assume that every worker inelastically supplies all of their time for working. Hence, the worker's labor supply decision is only about allocating that time to a sector, occupation pair. Each worker chooses a pair of sector s and occupation o to maximize her potential labor income conditional on her $(S \times O)$-dimensional productivity matrix ϵ. In other words, worker's problem can be written as

$$\max_{s,o} w_i^{s,o}\epsilon^{s,o},$$

where $w_i^{s,o}$ is per-unit wage for workers in sector s of country i with occupation o. Workers take the per-unit wages as given. Since ϵ is randomly drawn from a joint Fréchet distribution $G_t(\epsilon)$, the equilibrium labor supply decision for workers of type t for sector s and occupation o is

$$\pi_{i,t}^{s,o} = \frac{T_t^{s,o}(w_i^{s,o})^{\theta_t}}{\sum_{s',o'} T_t^{s',o'}(w_i^{s',o'})^{\theta_t}}.$$

The shape parameter θ_t for type t workers' productivity distribution is thus the labor supply elasticity of type t workers at the sector and occupation level. Different worker types are allowed to potentially have different labor supply elasticity in this model. Conditional on the optimal labor supply decision, the equilibrium average wage of type t workers can be derived as

$$\bar{w}_{i,t} = [\sum_{s',o'} T_t^{s',o'} (w_i^{s',o'})^{\theta_t}]^{1/\theta_t} \Gamma(1 - \frac{1}{\theta_t}).$$

If we define worker types based on educational attainment, the relative $\bar{w}_{i,t}$ of high-skilled workers over low-skilled workers will be a model counterpart of the skill premium, which will be one of our core objects of interest in the quantitative exercises.

2.4 General Equilibrium

The equilibrium per-unit wages $w_i^{s,o}$ and the prices P_i^s are solved in general equilibrium from market clearing conditions for each occupation. We have occupation market clearing conditions for each country, sector, and occupation:

$$\sum_t \bar{w}_{i,t} \pi_{i,t}^{s,o} \bar{L}_{i,t} = \alpha_i^s \sum_j \gamma^{s,j} \tilde{\gamma}^{s,j} \beta_i^{j,o} b^s \sum_{n=1}^{N} \sum_{l \in \Lambda_i^j} \lambda_{l,n}^s (\sum_t \bar{w}_{n,t} \bar{L}_{n,t} + \sum_{s'} \frac{(1-\alpha_n^{s'})}{\alpha_n^{s'}} \sum_o \sum_t \bar{w}_{n,t} \pi_{n,t}^{s',o} \bar{L}_{n,t}), \tag{2}$$

where we define

$$\Lambda_i^j \equiv \{l = (l^1, \dots, l^J) \in \mathbf{N}^J | l^j = i\}$$

as the set of GVC that produces j-th stage in country i. The left-hand side of this occupation market clearing condition is the total labor income earned by workers in sector s of country i with occupation o. This term should be equal to the right-hand side, which is the total payment for those specific workers. The goods market clearing condition is embedded in the share of sector s in total income on the right-hand side.

Let us now discuss the components of the right-hand side in more detail. A key part of the right-hand side is total spending from the countries "purchasing" the goods and services produced by the particular country-sector-occupation. This spending is then multiplied by a factor related to the roundabout nature of production, which is in turn multiplied by the probability $\lambda_{l,n}^s$ that country i is producing stage j of a GVC that winds up in the purchasing country. This term is then multiplied by the sectoral consumption share, so we now have total spending on the particular stage and sector, controlling for roundabout effects. This is then multiplied by the value-added component of this spending, which is the product of the relevant α, γ, and β terms. Finally, the right-hand side is summed over all stages of production.

To solve the model, we first normalize the wages to satisfy $\sum_{i,s,o} w_i^{s,o} = 1$. With this normalization, and with the occupation market clearing conditions and the exact price index as derived above, we can solve the model for the equilibrium $w_i^{s,o}$ and P_i^s using the

Alvarez and Lucas (2007) algorithm. We first guess initial $w_i^{s,o}$ and solve for P_i^s following equation (1). With the initial guess of $w_i^{s,o}$ and the solved P_i^s, we calculate all equilibrium variables of the model to construct the occupation market clearing conditions (2). We then update $w_i^{s,o}$ according to the excess demand or supply of labor calculated from (2). Iterations continue until the excess occupational demand or supply is sufficiently close to zero.

2.5 Discussion

The core mechanism of our model is the interaction between country-level comparative advantage (*the Ricardian and HO channels*) and worker-level comparative advantage (*the Roy channel*) along the GVC. If trade costs change in this economy, the relative demands for country i's intermediate materials and final goods change in all sectors, which, in turn will affect each country's specialization pattern across sectors and stages. These changes in specialization patterns, in conjunction with the relative occupation intensity of each production stage and the sector-specific GVC intensities, induce changes in the relative demand for occupations. This labor demand shock, in turn, affects sector- and occupation-specific per-unit wages. Workers then re-optimize their choice of sector and occupation. Even though workers observe the same change in wages for each sector and each occupation, the individual worker's response will differ depending on his/her idiosyncratic productivity.

We now turn to discussing how particular parameters of the model map into comparative advantage. For countries, there is comparative advantage at the sector-level and at the stage-level. Sector-level comparative advantage of countries is based primarily on the relative magnitude of A_i^s. Relative endowment also shapes sector-wise comparative advantage of countries through $\bar{L}_{i,t}$ and $T_{i,t}^{s,o}$, because sectors also use different occupations with different intensities based on $\beta^{j,o}\alpha_i^s\gamma^{s,j}$. Hence, if both α_i^s and $\gamma^{s,j}$ are the same across sectors, then sector-level comparative advantage of countries is entirely determined by the Ricardian channel.

Stage-level comparative advantage of countries is driven primarily from the HO force through the relative endowment governed by $\bar{L}_{i,t}$ and $T_{i,t}^{s,o}$, and the occupation intensity $\beta^{j,o}$. The Ricardian channel also shapes the stage-level comparative advantage through the interaction between A_i^s and $\gamma^{s,j}$. Similarly to the sector-level comparative advantage, if $\gamma^{s,j}$ does not vary by sector, then the stage-level comparative advantage is determined entirely by the HO force. Therefore, in the most general case without any restriction on the model parameters, we can have both sector-wise and stage-wise comparative advantages, each of which is affected by both the Ricardian and the HO forces as explained above.

How does the Roy channel of our model work? There are two Roy effects. The first is that the combination of $\bar{L}_{i,t}$ and $T_t^{s,o}$ determine the effective labor endowment, which affects country-level comparative advantage across sectors and stages. Note that here, there is overlap between the Roy and HO channels. Second, when the trade environment changes, this Roy channel operates by generating different labor reallocation patterns across different worker types. Even though workers face the same trade shock, they may end up at different sectors and occupations depending on their own comparative advantages.

To understand how these interactions work, it will be useful to start with a special case in which the Roy channel is not operative. The following assumptions bring our model closer to standard trade models without endogenous labor supply:

1. $\theta_t \rightarrow \infty$ for all worker types. In this case, workers have the same productivity conditional on their type and their choice of sector and occupation.

2. Occupations and worker types are identical, i.e., $T = O$.

3. $T_t^{s,o} \rightarrow 0$ for every $o \neq t$ and $T_t^{s,t} = 1$ for all s and t.

Under these assumptions, type t workers will always choose occupation t, because the variance of the productivity distribution goes to 0 as $\theta_t \rightarrow \infty$. Also, the assignment of worker types into sectors is entirely determined by relative wages as in standard trade models without endogenous labor supply.

The nature of the sourcing decision does not change when we shut down the Roy channel. Because we have a one-to-one mapping between worker types and occupations and workers of same type have the same productivity for different sectors, type-level wages are equalized across sectors. Thus, we have $N \times T = N \times O$ wage variables w_i^t and the same number of labor market clearing conditions. Without the Roy channel, exogenous labor endowments and stage-specific factor intensities entirely determine relative wages across different worker types in a similar way as in the standard HO model. However, this standard model is not able to capture the channel that workers of the same type may move to the same sector, but choose different occupations within that sector. If we have an exact one-to-one mapping between worker types and occupations and assume that these are exogenously fixed as in standard trade models, then workers are not allowed to switch their occupation as they switch their sector affiliation. We show later in this paper that deviating from the standard HO model, i.e., having the Roy channel, is quantitatively relevant.

In order to further study the effect of GVC, we need to focus on the role of $\gamma^{s,j}$. $\gamma^{s,j}$ captures the relative importance of the "roundabout" structure over the "snake" structure. Because $(1-\gamma^{s,j})$ denotes the share of stage $j-1$ used for production of stage j in sector s, the sequential structure of production through GVC becomes less important as $\gamma^{s,j} \to 1$. In the extreme case where $\gamma^{s,j} = 1$ for all $j = 1, \ldots, J$, only stage J production remains active using only domestic labor inputs and composite intermediates of finished goods through the roundabout structure. Our baseline model is then equivalent to the multi-sector EK model with intermediate inputs.

As discussed in many papers in the literature including Yi (2003; 2010) and Johnson and Noguera (2012), introducing GVCs into standard trade models can yield magnified effects of changes in trade costs on aggregate outcomes such as bilateral and aggregate trade flows and prices. Our result is in line with the prediction on the magnification effect from the literature. As $\gamma^{s,j} \to 0$, production stages become more inter-dependent, and the effective trade elasticity $\nu\tilde{\gamma}^{s,j}$ becomes larger. Thus, aggregate effects from trade liberalization are increasingly magnified with GVC intensity.

By contrast, the distributional effect of a reduction in trade costs is not monotonic in GVC intensity. It is straightforward that the HO channel diminishes as $\gamma^{s,j} \to 0$ in all sectors and stages, where the baseline model depends only on a product of random stage-specific productivities. This case features the full snake structure. However, occupation intensity does not matter in this case, because labor provides no value-added even from the first stage. As $\gamma^{s,j} \to 1$ in all sectors and stages, the difference in occupation intensity across production stages becomes also irrelevant, since previous-stage materials are almost not used in immediately following stages. As a consequence, a reduction in trade costs has very small effects on between-worker-type inequality–e.g., the skill premium–, if a trade model features either the full roundabout structure ($\gamma^{s,j} \to 1$) or the full snake structure ($\gamma^{s,j} \to 0$).

If two sectors have the same $\gamma^{s,j}$ for all upstream stages up to $j = j'$ but one sector has larger values of $\gamma^{s,j}$ for all downstream stages $j = j'+1, \ldots, J$, then, in that sector, the GVC intensity $(1-\gamma^{s,j})$ becomes smaller as we go downstream. Trade shocks would have smaller effects on aggregate outcomes in that sector, such as trade flows and prices. This is because the effective trade elasticity of upstream stages $\nu\tilde{\gamma}^{s,j}$ in this sector is discounted more with a larger downstream $\gamma^{s,j}$, which makes the overall trade elasticity smaller for this sector. In addition, occupations that are used more intensively in upstream stages will get relatively smaller weights in this sector, because $\gamma^{s,j}\tilde{\gamma}^{s,j}$ is smaller in upstream stages of this sector. On the other hand, occupations that are used intensively in downstream stages will get larger weights in this sector. Weights on stages will be reversed for the other sector with lower $\gamma^{s,j}$ for all downstream stages $j = j' + 1, \ldots, J$. Therefore, variation in GVC intensity $\gamma^{s,j}$ across sectors puts different weights on labor demand shifts across sectors and stages. We will further discuss interaction of distributional effects of trade with the GVC intensity using a simple 2-stage version of our model in the next section.

3 A Simple 2-Stage Model

In this section, we simplify our baseline model to 2 production stages, 2 countries, 2 worker types, 2 sectors, and 2 occupations in order to show the underlying mechanism intuitively. We then perform numerical exercises with this simple 2-stage model.

3.1 Model Setup and the Equilibrium

We denote countries by $i = 1, 2$, worker types by $t = H, L$, and production stages by $j = 1, 2$. As in the baseline model, worker types are exogenously given from workers' perspective, while workers are allowed to endogenously choose sector $s = 1, 2$ and occupation $o = H, L$. Labor supply at the worker type level is thus exogenously fixed: $\bar{L}_{1,H}$, $\bar{L}_{1,L}$, $\bar{L}_{2,H}$, and $\bar{L}_{2,L}$. In this simple 2-stage case, production functions for each stage are given by:

$$\begin{aligned} f_i^{s,1}(x_i^{s,1}, L_i^{s,1,H}(\omega), L_i^{s,1,L}(\omega)) &= z_i^{s,1}(\omega)(x_i^{s,1})^{1-\alpha_i^s}((L_i^{s,1,H}(\omega))^{\beta^{1,H}}(L_i^{s,1,L}(\omega))^{\beta^{1,L}})^{\alpha_i^s} \\ f_i^{s,2}(x_i^{s,2}, L_i^{s,2,H}(\omega), L_i^{s,2,L}(\omega), m_i^{s,1}(\omega)) &= z_i^2(\omega)[(x_i^{s,2})^{1-\alpha_i^s}((L_i^{s,2,H}(\omega))^{\beta^{2,H}}(L_i^{s,2,L}(\omega))^{\beta^{2,L}})^{\alpha_i^s}]^{\gamma^s} \\ &\quad \times (m_i^{s,1}(\omega))^{1-\gamma^s}. \end{aligned}$$

The occupation intensity parameters β's, along with the relative type-level labor endowments, generate the HO mechanism.[2] If $\frac{\beta^{1,H}}{\beta^{1,L}} > \frac{\beta^{2,H}}{\beta^{2,L}}$, for example, stage 1 production uses H occupations more intensively than does stage 2 production. Stage 2 producers of product ω use domestic labor, the composite intermediate (from the roundabout structure), and stage 1 material of product ω to produce final goods. The overall GVC intensity decreases in γ^s, the value-added share at stage 2, in each sector s. Netting out final goods used to make the composite intermediate through the roundabout production structure, the effective value-added share of stage 2 in sector s is $\gamma^s(\beta^{2,H} + \beta^{2,L})$. The stage 1 good that stage 2 producers of sector s in country i use is denoted by $m_i^{s,1}(\omega)$. The stage 1 good can be sourced either domestically or from another country $i' \neq i$ through GVC.

[2]Note that in this simplified model β does not vary by country.

The stage-specific factor-neutral productivity again follows the Fréchet distribution: for each country $i = 1, 2$,

$$z_i^{s,1}(\omega) \sim F_i^{s,1}(z) = \exp(-A_i^s z^{-\nu(1-\gamma^s)})$$

$$z_i^{s,2}(\omega) \sim F_i^{s,2}(z) = \exp(-A_i^s z^{-\nu}).$$

Similarly to our baseline model, the dispersion parameter of stage 1 is weakly smaller than that of stage 2 in every sector. This assumption will again capture the magnification effect of GVC, as we go to the downstream stages. We also maintain the sequential independence and the limited information assumptions of Antras and de Gortari that final good consumers in this 2-stage setup do not know the exact productivity draw of stage 1 producers.

The choice set for workers consists of four sector-occupation pairs. Given per-unit wage variables $w_i^{s,o}$, workers choose one among $(s, o) = (1, H), (1, L), (2, H), (2, L)$ to maximize their potential labor income conditional on their idiosyncratic productivities randomly drawn from a type-specific distribution. The equilibrium solution of the worker's problem yields the same expressions for $\pi_{i,t}^{s,o}$ and $\bar{w}_{i,t}$ as in the baseline model.

The sourcing decision for stage 2 producers of sector s in country i can be written as

$$l_i^{s,1}(\omega) = \arg\min_l [(p_l^{s,1}(\omega)\tau_{li}^s)^{1-\gamma^s}] = \arg\min_l [(\frac{c_l^{s,1}}{z_l^{s,1}(\omega)}\tau_{li}^s)^{1-\gamma^s}],$$

where $c_i^{s,1} \equiv \varphi_i^{s,1}(P_i)^{1-\alpha_i^s}[(w_i^{1,H})^{\beta^{1,H}}(w_i^{1,L})^{\beta^{1,L}}]^{\alpha_i^s}$, and $\varphi_i^{s,1}$ is a Cobb-Douglas constant as defined in the general version of the model. Similarly, the sourcing decision for final good consumers in country i is

$$l_i^{s,2}(\omega) = \arg\min_l [\frac{(c_l^{s,2})^{\gamma^s}}{z_l^{s,2}(\omega)} \times \Theta_l^s \times \tau_{li}^s],$$

where $\Theta_l^s \equiv E[(p_{l_l^{s,1}(\omega)}^{s,1}(\omega)\tau_{l_l^{s,1}(\omega),l}^s)^{1-\gamma^s}]$, and $l_l^{s,1}(\omega)$ is the optimal source of stage 1 of sector-s product ω for stage 2 producers of sector s in country l. The unit cost for stage 2 of sector s is given by $c_i^{s,2} \equiv \varphi_i^{s,2}(P_i)^{1-\alpha_i^s}[(w_i^{2,H})^{\beta^{2,H}}(w_i^{2,L})^{\beta^{2,L}}]^{\alpha_i^s}$ for a stage-2 Cobb-Douglas constant $\varphi_i^{s,2}$.

Because we assume that productivities are drawn from country- and sector- and stage-specific Fréchet distributions, the above sourcing problems imply the following bilateral

GVC probabilities:

$$\Pr(l_i^{s,1}(\omega)=n)=\frac{A_n^s(c_n^{s,1}\tau_{ni}^s)^{-\nu(1-\gamma^s)}}{\sum_{n'}A_{n'}^s(c_{n'}^{s,1}\tau_{n'i}^s)^{-\nu(1-\gamma^s)}}$$

$$\Pr(l_i^{s,2}(\omega)=n)=\frac{A_n^s((c_n^{s,2})^{\gamma^s}\Theta_n^s\tau_{ni}^s)^{-\nu}}{\sum_{n'}A_{n'}^s((c_{n'}^{s,2})^{\gamma^s}\Theta_{n'}^s\tau_{n'i}^s)^{-\nu}}.$$

Using the independence assumption for stage-specific productivity draws, the sourcing decision, and limited information across stages, the equilibrium probability that a sector-s product consumed by country i consumers follows a specific GVC $l=(l^1,l^2)$ is given by:

$$\lambda_{l,i}^s=\frac{A_{l^1}^s(c_{l^1}^{s,1}\tau_{l^1l^2}^s)^{-\nu(1-\gamma^s)}\times A_{l^2}^s[(c_{l^2}^{s,2})^{\gamma^s}\tau_{l^2i}^s]^{-\nu}}{\sum_{l'\in\mathbf{N}^2}A_{l'^1}^s(c_{l'^1}^{s,1}\tau_{l'^1l'^2}^s)^{-\nu(1-\gamma^s)}\times A_{l'^2}^s[(c_{l'^2}^{s,2})^{\gamma^s}\tau_{l'^2i}^s]^{-\nu}},$$

where $\mathbf{N}^2=\{(l_1,l_2):(1,1),(1,2),(2,1),(2,2)\}$. As in the baseline model, the effective trade elasticity varies by production stage. We have a larger effective trade elasticity for final goods than for stage 1 goods for every sector.

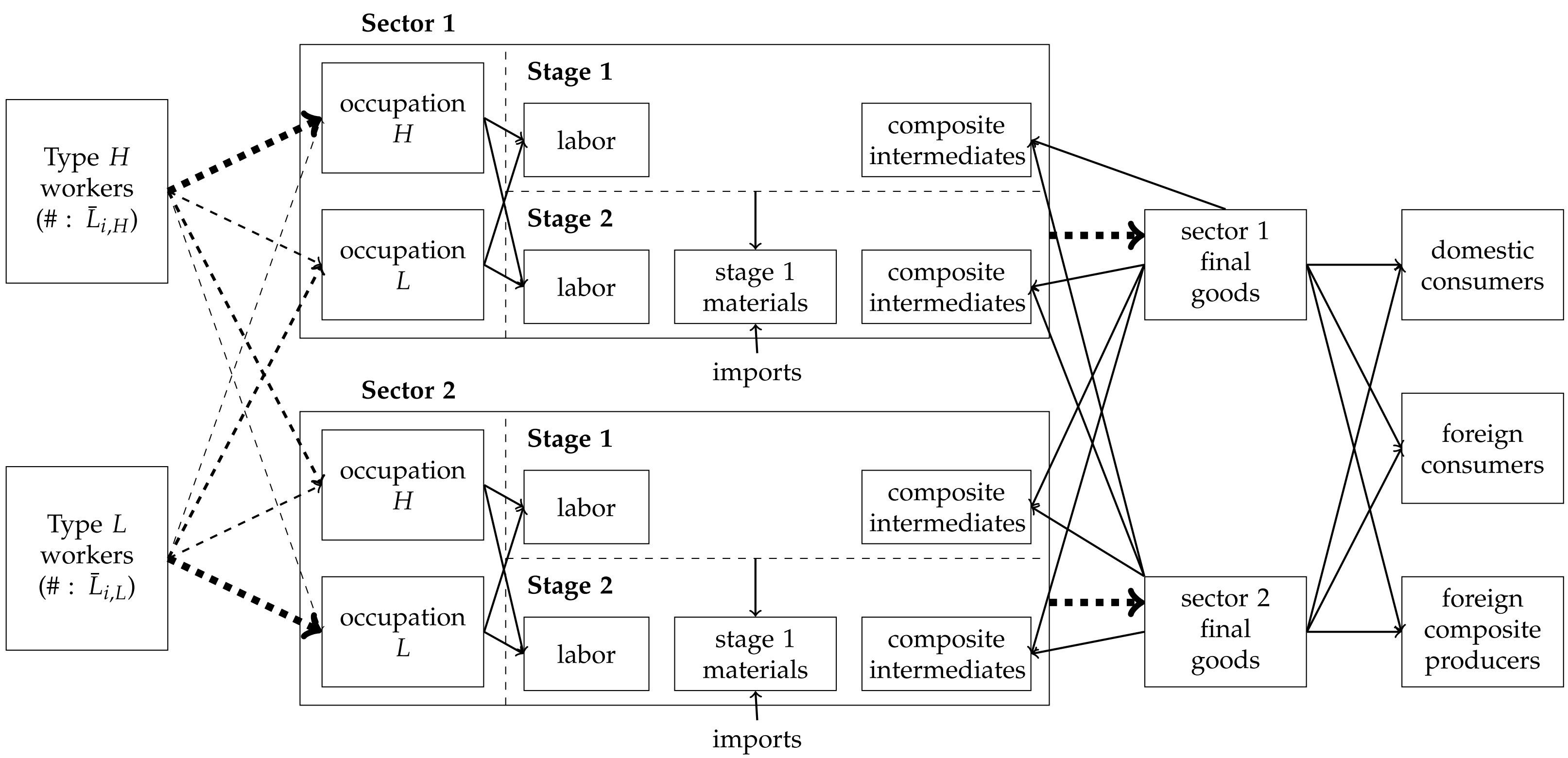
In general equilibrium, all markets clear. We have eight labor market clearing conditions for the $2\times2\times2$ countries, sectors, and occupations. For each country $i=1,2$, sector $s=1,2$, and occupation $o=H,L$, the labor market clearing conditions are

$$\begin{aligned}\sum_t\bar{w}_{i,t}\pi_{i,t}^{s,o}\bar{L}_{i,t} &= (1-\gamma^s)\beta^{1,o}\alpha_i^s b^s\sum_{n=1}^{N}\sum_{l\in\Lambda_i^1}\lambda_{l,n}^s(\sum_t\bar{w}_{n,t}\bar{L}_{n,t}+\sum_{s'}\frac{(1-\alpha_n^{s'})}{\alpha_n^{s'}}\sum_o\sum_t\bar{w}_{n,t}\pi_{n,t}^{s',o}\bar{L}_{n,t})\\ &\quad+\gamma^s\beta^{2,o}\alpha_i^s b^s\sum_{n=1}^{N}\sum_{l\in\Lambda_i^2}\lambda_{l,n}^s(\sum_t\bar{w}_{n,t}\bar{L}_{n,t}+\sum_{s'}\frac{(1-\alpha_n^{s'})}{\alpha_n^{s'}}\sum_o\sum_t\bar{w}_{n,t}\pi_{n,t}^{s',o}\bar{L}_{n,t})\end{aligned}$$

where $\Lambda_i^1,\Lambda_i^2\in\mathbf{N}^2$ are defined as in the baseline model.

Figure 1 describes the structure of this 2-stage model. For country i, there are $\bar{L}_{i,H}$ type H workers and $\bar{L}_{i,L}$ type L workers. These workers endogenously choose a sector and an occupation to maximize their labor income based on their productivity draws; this choice is described by the dashed arrows on the left. Owing to worker-based comparative advantage forces, the choice of occupations and sectors should differ across worker types. Within each sector, occupational tasks are allocated to the two production stages based on the relative magnitude of the occupation intensity between the stages. Combining the labor input in the two occupations H and L with the composite intermediate (again, this is a CES aggregate of the final goods), stage 1 producers produce their specific stage 1 goods.

Figure 1: A 2-stage GVC Model with Endogenous Labor Supply



Each stage 1 good is then used either by its counterpart stage 2 producer in the same country i or, via export, its corresponding stage 2 producer in the foreign country. Stage 2 producers then combine labor input in the two occupations H and L, the composite intermediate, and the stage 1 good to produce the final goods. As a reminder, there is a one-to-one mapping from the stage 1 producer of a good ω to the stage 2 producer of ω – this is the snake mechanism. Finally, domestic and foreign consumers purchase the final goods. Domestic and foreign producers of every stage in every sector also use these final goods as composite intermediates.

We focus our discussion of the 2-stage model on the implications for the skill premium and the role of the GVC intensity $1 - \gamma^s$ in affecting the change in the skill premium when trade costs decline. When trade costs decline, countries specialize further in their comparative advantage sector and stage. The occupation intensity $\beta^{j,o}$ first determines how much each occupation is used at each production stage. Combined with the GVC intensity γ^s, it also determines how much of sector-wise specialization affects occupation-level labor demand. This channel is similar to the standard HO mechanism in which factor intensity determines labor demand shifts and eventually wage changes. Our model features this standard channel across both stages and sectors.

While predictions on the skill premium from standard trade models depend almost entirely on the factor intensity, our GVC model shows that interaction between the occupation intensity and the GVC intensity matters when predicting distributional impacts of trade. This simple 2-stage model is useful to investigate the role of GVC intensity. We can think of two special cases regarding γ^s to further explore the role of GVC intensity for the skill premium. First, if we maintain the sectoral variation of GVC intensity–i.e., $\gamma^1 \neq \gamma^2$, trade shocks will change the skill premium by a smaller amount when the average level of γ^1 and γ^2 is extreme. As we can see from the set of labor market clearing conditions above, extreme values of γ^s (i.e., close either to 0 or to 1) make this 2-stage model essentially a one-stage model in terms of distributional effects of trade. If γ^1 and γ^2 are close to 1, then stage 2 producers of both sectors do not use the stage 1 good for final goods production. Thus, the relative factor intensity of stage 1 does not generate distributional effects from a reduction in trade costs. If γ^1 and γ^2 are close to 0 in all sectors, on the other hand, the relative factor intensity of stage 2 becomes irrelevant in all sectors, because labor has almost no value-added in stage 2 production.

Another special case is when γ^s puts higher weights on each country's comparative advantage sector and stage. In this case, the effect of trade shocks on the skill premium will be larger in magnitude, because country-level comparative advantage shifts labor demand much more. In section 2.5, we discussed this mechanism through which GVC intensities put different weights on different stages and sectors based on the general version of our model. While this mechanism is not straightforward in the general case in which we need to consider $\gamma^{s,j}\tilde{\gamma}^{s,j}$ for all sectors and stages, the 2-stage case of our model shows this relationship more clearly, because it is based only on γ^s and $(1-\gamma^s)$. These are the weights put on stage and sector, as can be seen from the occupation market clearing condition in our 2-stage model. If a country has a comparative advantage in stage 1 and sector 1 and γ^1 is very low, occupations that are used intensively in stage 1 will get larger positive demand shifts when this country specializes in their comparative advantage stage and sector. In other words, in addition to the relative occupation intensity $\beta^{j,o}$, the value-added that each stage provides to the entire production chain matters for how much trade shocks affect the skill premium.

This result is in sharp contrast with the aggregate effects of lower trade costs, which are increasingly magnified as γ^s decreases. When $\gamma^s \to 0$ for all $s = 1, 2$, our model has only the pure snake channel of trade in intermediates. Thus, the effect of a reduction in trade costs on aggregate trade flows has the maximum magnification.

In summary, a simple 2-stage case of our model reiterates the importance of having an accurate measure of sector-level GVC intensity when we investigate the effect of GVC on inequality. Even though aggregate effects are monotonically magnified with a larger GVC intensity, distributional effects of GVC will not be monotonic in GVC intensity. In addition, sector-level variation in the GVC intensity is important for the magnitude of the Ricardioan, HO and Roy effects.

3.2 Numerical Analysis

In this section, we solve the simple 2-stage case of our baseline model numerically. In order to lay out the core mechanism more clearly, we assign parameter values so that only the HO comparative advantage operates across countries. In other words, countries have different endowments of type-level labor, but the scale parameters of the distribution of factor-neutral productivity are assumed to be the same across countries and sectors.

Thus, the numerical example we consider satisfies: 1) country 1 is relatively more abundant in type L workers– i.e., $\frac{\bar{L}_{1,H}}{\bar{L}_{1,L}} < \frac{\bar{L}_{2,H}}{\bar{L}_{2,L}}$; 2) stage 1 uses L occupations relatively more intensively than does stage 2– i.e., $\frac{\beta^{1,L}}{\beta^{1,H}} > \frac{\beta^{2,L}}{\beta^{2,H}}$; 3) type L workers have comparative advantage in sector 1 and in L occupations– i.e., $\frac{T_H^{1,o}}{T_H^{2,o}} < \frac{T_L^{1,o}}{T_L^{2,o}}$ for every o and $\frac{T_H^{s,L}}{T_H^{s,H}} < \frac{T_L^{s,L}}{T_L^{s,H}}$ for every s; and 4) sector 1 depends more on stage 1 production than sector 2 does– i.e., $\gamma^1 < \gamma^2$. The first and second conditions imply HO comparative advantage across countries. The third condition describes the Roy channel of our model, and it assumes that the Roy channel does not reverse the HO comparative advantage. The last condition also assumes that the sectoral variation in the GVC intensity does not reverse the HO comparative advantage. In summary, country 1 is abundant in type L workers and thus have a comparative advantage in sector 1 and stage 1 where L occupations are relatively more important, because type L workers have comparative advantage in L occupations.

Based on these conditions, we assign the following values for our benchmark numerical exercise: 1) Ricardian comparative advantage parameter $A_i^s = 1$ for all i and s; 2) type-level labor supply $(\bar{L}_{1,H}, \bar{L}_{1,L}, \bar{L}_{2,H}, \bar{L}_{2,L}) = (0.3, 0.7, 0.7, 0.3)$; 3) occupation intensity for each productions stage $(\beta^{1,H}, \beta^{1,L}, \beta^{2,H}, \beta^{2,L}) = (\frac{1}{3}, \frac{2}{3}, \frac{2}{3}, \frac{1}{3})$; 4) the scale parameter of workers' productivity distribution $(T_H^{1,H}, T_H^{1,L}, T_H^{2,H}, T_H^{2,L}) = (3, 1, 4, 2)$ and $(T_L^{1,H}, T_L^{1,L}, T_L^{2,H}, T_L^{2,L}) = (2, 4, 1, 3)$; and 5) $\gamma^1 = 0.3$ and $\gamma^2 = 0.7$.

Because the GVC intensity parameter γ^s plays an important role in our model for both aggregate and distributional effects of reduction in trade costs, we will experiment with different values of γ^s and with a sector-level variation in γ^s later in this section. For the elasticity parameters, we set $\nu = 4$ (a common component of trade elasticity across productions stages), $\sigma = 2$ (elasticity of substitution across products in preference), and $\theta_t = 2$ for all t (labor supply elasticity.) The labor supply elasticity parameter is allowed to be different across worker types in a general version of our baseline model. While we consider a case where two worker types share the same labor supply elasticity in this numerical exercise, we will estimate this parameter separately for different worker types in the full quantification of our model. Lastly, consumers are assumed to have the same expenditure share between sectors in their preference– i.e., $b^1 = b^2 = 0.5$, and the value-added shares are the same across all sectors and countries–i.e., $\alpha_i^s = 0.3$ for all i and s.

We compare the case with $\tau_{in}^s = 2$ for $i \neq n$ and $\tau_{ii}^s = 1$ ("high trade cost case") to a "free trade case" with $\tau_{in}^s = 1$ for all i, n. In the benchmark simulation, we consider the same change in trade costs across two sectors. Given trade costs and parameter values, we solve the occupation market clearing conditions and the exact price indices for the equilibrium $w_i^{s,o}$ and P_i^s following the Alvarez and Lucas (2007) algorithm. We also normalize wages to satisfy $\sum_{i,s,o} w_i^{s,o} = 1$.

Benchmark Results Once we solve for the equilibrium $w_i^{s,o}$ and P_i^s, we then calculate type-level average wages $\bar{w}_{i,t}$, within-worker-type labor allocation across sectors and occupations $\pi_{i,t}^{s,o}$, unit cost for sector- and stage-specific input bundles $c_i^{s,j}$, and the GVC flows $\lambda_{l,i}^s$ as functions of $w_i^{s,o}$ and P_i^s. Distributional effects of reduction in trade costs are measured by changes in the skill premium from the high trade cost case to the free trade case. We define the skill premium by $SP_i = \bar{w}_{i,H} / \bar{w}_{i,L}$.

A reduction in trade costs enables producers to source intermediates from the lowest cost supplier and also enables consumers to purchase final goods from the lowest cost producer. Conseqently, not surprisingly, as trade costs fall to zero, the aggregate price index decreases in each country– by 91% in country 1 and by 89% in country 2. In both countries, the sector 1 price index declines more than the sector 2 price index, because, with $\gamma^1 < \gamma^2$, sector 1 depends more on GVC. To further understand this result, it is useful to look at Table 1, which presents the GVC probability $\lambda^s_{l,i}$ for both trade cost cases. Table 1 also shows the changes in $\lambda^s_{l,1}$ and $\lambda^s_{l,2}$, as we move from $\tau^s_{in} = 2$ for $i \neq n$ to $\tau^s_{in} = 1$ for all i and n in both sectors $s = 1, 2$.

Table 1: Changes in $\lambda^s_{l,i}$ from the Benchmark Simulation

		(1) $\tau^s_{in} = 2$		(2) $\tau^s_{in} = 1$		(3) change (pp)	
		$l_2 = 1$	$l_2 = 2$	$l_2 = 1$	$l_2 = 2$	$l_2 = 1$	$l_2 = 2$
$\lambda^1_{l,1}$	$l_1 = 1$	0.837	0.008	0.264	0.265	-57	26
	$l_1 = 2$	0.108	0.048	0.235	0.236	13	19
$\lambda^2_{l,1}$	$l_1 = 1$	0.644	0.021	0.236	0.265	-41	24
	$l_1 = 2$	0.286	0.049	0.235	0.264	-5	22
$\lambda^1_{l,2}$	$l_1 = 1$	0.056	0.129	0.264	0.265	21	14
	$l_1 = 2$	0.007	0.808	0.235	0.236	23	-57
$\lambda^2_{l,2}$	$l_1 = 1$	0.034	0.284	0.236	0.265	20	-2
	$l_1 = 2$	0.015	0.666	0.235	0.264	22	-40

In the high trade cost case described in the first panel of the table, both countries mostly source stage 1 materials and final goods domestically. In sector 1, about 83.7% of final goods consumed in country 1 follow a GVC $(l_1, l_2) = (1, 1)$, and 80.8% of final goods consumed in country 2 follow $(l_1, l_2) = (2, 2)$. High trade costs keep countries from specializing in their comparative advantage stages, and thus, countries tend to source both stages domestically.

When trade costs are uniformly reduced to zero, i.e., $\tau_{in} = 1$ for all i and n, then it is most likely that a final good follows the GVC of country-level comparative advantage, $(l_1, l_2) = (1, 2)$. About 26.5% of final goods follow the GVC $(l_1, l_2) = (1, 2)$ in both sectors regardless of the location of final goods consumers, because there is no trade cost. Despite the presence of free trade, complete specialization does not occur owing to heterogeneity in productivity within each sector and each stage. In percentage points, the largest decline of the GVC share is from the domestic sourcing case in both sectors–$(l_1, l_2) = (1, 1)$ for final goods consumers in country 1 and $(l_1, l_2) = (2, 2)$ for final goods consumers in country 2–when we move from the high trade cost case to the free trade case. Domestic sourcing decreases more in sector 1, because sector 1 depends more on stage 1 materials with lower γ^1. Therefore, the effective trade elasticity for stage 1 materials is higher in sector 1.

Note that under free trade, the most prevalent GVC is the one in which stage 1 is made in country 1 and stage 2 is made in country 2 in both sectors. To serve consumers in country 1, the stage 2 goods produced in country 2 are shipped back to country 1 for its consumers. But, under high trade costs, this GVC becomes especially costly, because it involves two border crossings. Consequently, this GVC falls almost to a zero share. Country 1 has to substitute high cost alternatives as a result. Essentially, the upstream nature of country 1's specialization makes it more costly to engage in a GVC under high trade costs. Hence, country 1's price index is high relative to country 2's under such costs.

The reduction in trade costs changes the skill premium in the direction predicted by the Stolper-Samuelson theorem. Our benchmark parameter values assume that: 1) sector 1 depends relatively more on stage 1; 2) stage 1 uses occupation L more intensively; 3) type L workers have comparative advantage in sector 1 and in occupation L; and thus 4) country 1 has a comparative advantage in stage 1 and sector 1. Therefore, as trade costs go down, the relative demand for type H workers decreases in country 1 and increases in country 2. Our model predicts that the skill premium increases by 1.1% in country 2, and decreases by 1.1% in country 1, as we move from the high trade cost case to free trade. This numerical exercise is set up to highlight the Stolper-Samuelson effect through the GVC by assigning appropriate parameter values. In a more general setup, our model allows for non-Stolper-Samuelson effects as well depending on different values for key parameters $\gamma^{s,j}$, $\beta^{j,o}$, $\bar{L}_{i,t}$, $T_t^{j,o}$, and θ_t.

In response to the reduction in trade costs, the Roy channel of our model reallocates workers across sectors and occupations within their type. Workers may stay in the same sector, but move to a different occupation, an outcome not present in standard trade models with homogeneous workers. The within-type labor reallocation is measured by changes in $\pi_{i,t}^{s,o}$ as we move from high trade costs to free trade.

Table 2 first shows within-type labor allocation pattern predicted by our baseline model. First, the simulation results show that workers are more likely to work in their comparative advantage sector and with a comparative advantage occupation in both the high trade cost case and the free trade cost case. Second, even though a certain worker

Table 2: Changes in $\pi_{i,t}^{s,o}$ from the Benchmark Simulation

		(1) $\tau_{in}^{s}=2$		(2) $\tau_{in}^{s}=1$		(3) change (pp)	
	$\pi_{i,t}^{s,o}$	$o=L$	$o=H$	$o=L$	$o=H$	$o=L$	$o=H$
Country 1, Type H	$s=1$	0.081	0.255	0.084	0.261	0.3	0.6
	$s=2$	0.138	0.526	0.138	0.516	0.02	-0.9
Country 1, Type L	$s=1$	0.391	0.204	0.398	0.205	0.8	0.1
	$s=2$	0.248	0.157	0.244	0.152	-0.4	-0.5
Country 2, Type H	$s=1$	0.157	0.249	0.152	0.244	-0.5	-0.4
	$s=2$	0.204	0.390	0.205	0.398	0.08	0.8
Country 2, Type L	$s=1$	0.524	0.138	0.516	0.138	-0.8	-0.02
	$s=2$	0.256	0.081	0.261	0.084	0.5	0.3

type has a comparative advantage in a certain sector and a certain occupation on average, the within-type labor allocation does not involve complete specialization owing to within-type heterogeneity in productivity. For example, about 8.1% of type H workers in country 1 work in sector 1 in occupation L, even though type H workers have on average a comparative advantage in sector 2 and occupation H.

Table 2 also shows a different picture from predictions of standard trade models regarding worker's labor reallocation pattern in response to a reduction in trade costs. First, as countries further specialize in their comparative advantage sector in response to the reduction in trade costs, workers of both types move between sectors accordingly. In other words, as we move from high trade costs to free trade, both type H and L workers in country 1 work more in sector 1, while workers in country 2 work more in sector 2. Second, workers choose different occupations when they move between sectors in response to trade shocks. This pattern depends on worker-level comparative advantage for occupations. For example, while some of both type H and L workers in country 1 move from sector 2 to sector 1, type H workers in H occupations increase by 0.6 percentage points, and type H workers in L occupations increase by 0.3 percentage points within sector 1. By contrast, type L workers of country 1 in L occupations increase by 0.8 percentage points, and those type workers in H occupations increase by 0.1 percentage points, in sector 1. There is a similar pattern for country 2, where workers of both types are likely to move from sector 1 to sector 2, but with different occupations depending on their comparative advantage. To summarize, workers' endogenous labor supply choice at the sector and occupation level generates another important layer of labor reallocation that is not captured by standard trade models.

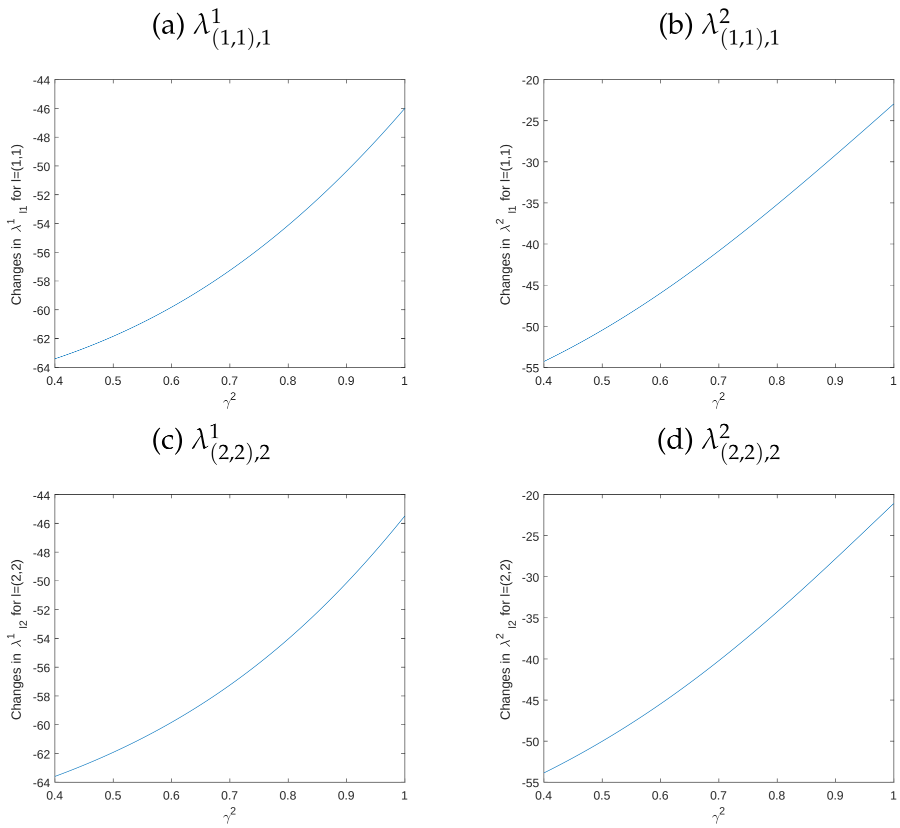
The Role of GVC Intensity The key parameter of our 2-stage model which governs the relative importance of the GVC or snake structure is $1-\gamma^s$ for each sector $s=1,2$. The effective GVC intensity, as well as the effective trade elasticity, decrease in γ^s, as stage 1 and stage 2 are less inter-dependent with a larger γ^s. In the extreme case $\gamma^s=1$, the effective trade elasticity for stage 1 is zero. In other words, the effects of the same change in trade costs will be different depending on the GVC intensity. If the GVC intensity is large–i.e., small γ^s–, effects of a reduction in trade costs are further magnified as noted in Yi (2003; 2010) and Johnson and Noguera (2012).

To illustrate these relationships, we repeat the baseline simulation with different values of γ^s, while keeping the baseline assumption that sector 1 depends more on stage 1. We conduct two exercises. In the first exercise, we assume $\gamma^2 \equiv \gamma$ and $\gamma^1=\gamma-0.4$ to have the same linear difference between γ^1 and γ^2 as in the baseline simulation. Then, we study different values of γ ranging from 0.4 to one to show how distributional effects of decline in trade costs vary by the GVC intensity. In the second exercise, we set $\gamma^2=0.5$, an average of two γ's in the baseline simulation, and vary γ^1 within $[\frac{\gamma^2}{2},\gamma^2]$ to investigate the effect of sectoral variation in γ^s.

The magnification effect through GVCs is illustrated in Figure 2 below, which shows changes in $\lambda^s_{(1,1),1}$ and $\lambda^s_{(2,2),2}$ for each sector $s=1,2$ when we move from the high trade cost case to the free trade cost case with different values of γ, where $\gamma^2\equiv\gamma$ and $\gamma^1=\gamma-0.4$. The GVC shares $\lambda^s_{(1,1),1}$ and $\lambda^s_{(2,2),2}$ are counterparts of domestic absorption share in standard trade models. If the hierarchical production structure through GVCs magnifies the effect of reduction in trade costs on trade flows, we should have larger decreases of $\lambda^s_{(1,1),1}$ and $\lambda^s_{(2,2),2}$ with lower values of γ. This implication can be drawn also from the larger decrease of domestic absorption in sector 1 of the baseline simulation compared to sector 2. Figure 2 clearly shows this magnification effect through GVC. While $\lambda^s_{(1,1),1}$ and $\lambda^s_{(2,2),2}$ decrease by about 46 percentage points in sector 1 and by 20 percentage points in sector 2 in response to the trade shock with γ^2 close to 1, the decreases are about 55-65 percentage points with γ^2 close to 0.4 (thus, γ^1 close to 0.) Therefore, multi-stage production and intermediate trade through GVC magnify the effect of the reduction in trade costs, and the magnification effect is monotonically increasing in the GVC intensity. Changes of all other aggregate variables from the model such as price index and other entries of the $\lambda^s_{l,i}$ matrices are also monotonic in γ: i.e., larger changes with lower γ.

The distributional effect of a reduction in trade costs, on the other hand, is not monotonic in the GVC intensity as predicted from our simulation. Figure 3 shows the change

Figure 2: Changes in $\lambda^{s}_{(1,1),1}$ and $\lambda^{s}_{(2,2),2}$ with Different Values of γ (%)



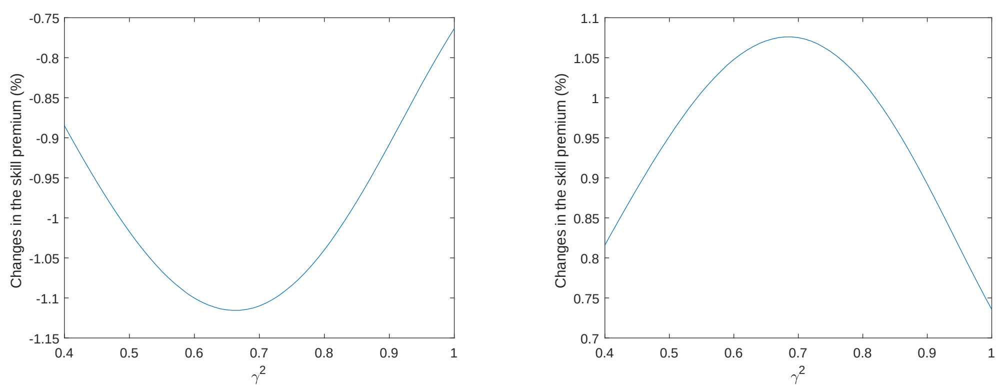
in the skill premium in each country when trade costs are eliminated under different values of γ, where $\gamma^2 \equiv \gamma$ and $\gamma^1 = \gamma - 0.4$. In this simple 2-stage case with only HO comparative advantage operative, the skill premium decreases in country 1 and increases in country 2 as a result of the reduction in trade costs for all values of γ. However, the magnitude of the change in the skill premium (resulting from the reduction in trade costs) is not monotonic in the GVC intensity – rather, it is largest at some intermediate values of average γ^s. This result shows that both the snake mechanism and the roundabout mechanism are important in understanding the effect of trade through GVCs on the skill premium.

If $\gamma^2 \to 1$ (therefore, $\gamma^1 \to 0.6$), the snake mechanism is shut down in sector 2 and also becomes less important in sector 1; the relative occupation intensity of stage 1 becomes irrelevant, because no stage 2 producers demand stage 1 materials. Therefore, changes in trade costs affect the skill premium much less in both countries. The effect is not entirely zero, because sector-level comparative advantage remains active. If we further simplify the model to a one-sector case, a decline in trade costs has no effect on the skill premium when $\gamma^2 \to 1$. In this case, the aggregate effects of a reduction in trade costs are also smallest, because there is no magnification effect through GVC.

On the other hand, if $\gamma^1 \rightarrow 0$ (therefore, $\gamma^2 \rightarrow 0.4$), only the snake mechanism is operative, and the relative factor intensity of stage 2 becomes close to irrelevant for sector 1. This is because there is little value added from labor in stage 2 production. Therefore, a reduction in trade costs changes the skill premium in both countries by a much smaller amount. Similarly to the one-sector version with $\gamma \rightarrow 1$, the distributional effect of a reduction in trade costs entirely vanishes in the one-sector version of our model with $\gamma \rightarrow 0$.

Figure 3: Changes in the Skill Premium with Different Values of γ (%)

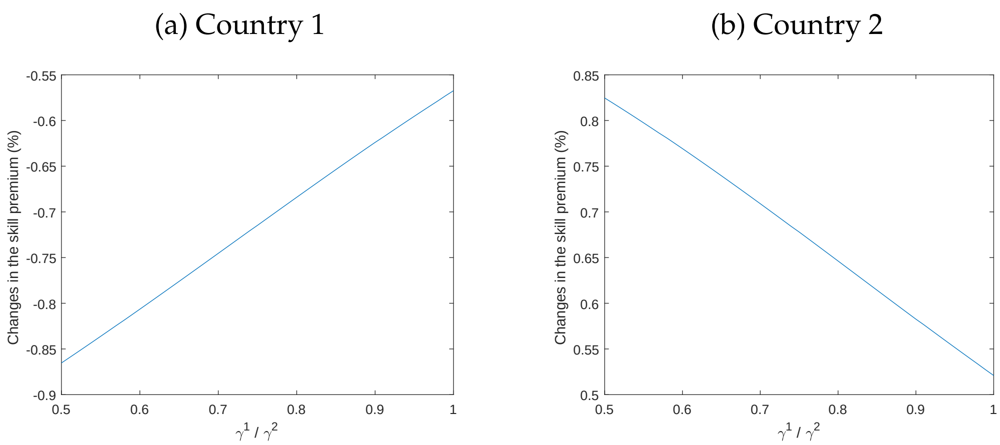
(a) Country 1 (b) Country 2



Our numerical exercise shows that a simple monotonic magnification effect does not apply for the distributional consequence of trade liberalization through GVC. The GVC intensity interacts with relative occupation intensity across production stages. The effect of a reduction in trade costs is largest with some intermediate value of $\gamma \in [0, 1]$ with which difference in relative occupation intensity are most pronounced across productions stages. This result suggests that GVCs transfer country-level comparative advantages to worker-level comparative advantages by putting different value-added weights on different production stages in different sectors. This mechanism makes the distributional impact of trade shocks non-monotonic in GVC intensities. Therefore, sectoral variation in the GVC intensity plays an important role. In our first exercise, the difference in γ^s between sector 1 and sector 2 was fixed.

To further explore the importance of sectoral variation in γ^s, we set $\gamma^2 = 0.5$ and explore different ratios $\gamma^1/\gamma^2 \in [0.5, 1]$ in our second exercise. Sector 1 depends relatively more on stage 1 as in the baseline simulation. As γ^1 gets smaller, we put larger weights on each country's comparative advantage sector, because our baseline parameter values assume that country 1 (country 2) has a comparative advantage in sector 1 and stage 1 (sector 2 and stage 2.) Figure 4 shows that the size of increase (decrease) of the skill premium in country 2 (country 1) is larger when γ^1 and γ^2 are further apart (geometrically). In our model, sectoral variation in the GVC intensity governs how much of country-level comparative advantage is transmitted into worker-level comparative advantage by putting different weights on each sector and each stage. Equivalently, it affects how much trade shocks affect relative gains among different types of workers. As long as the relative magnitude of the GVC intensity does not reverse the HO comparative advantage, i.e., $\gamma^1 < \gamma^2$ in this simple case, the effect of a decline in trade costs is larger the larger the weights on their comparative advantage stages are.

Figure 4: Changes in the Skill Premium with Different Values of γ (%)



In summary, the results from the numerical exercises show how the GVC mechanism and the Roy mechanism interact with standard HO comparative advantage. First, countries specialize in their comparative advantage production stage as trade costs go down, which shifts relative demand for occupations in our model. Second, depending on different GVC intensities across sectors, sector-level labor demand is also affected. Third, the Roy mechanism based on workers' heterogeneous productivities makes workers respond to trade shocks differently across sectors and occupations, even though workers are exposed to the same trade shock. Fourth, as predicted in existing papers in the literature, aggregate effects of reduction in trade costs on trade flows and prices are monotonically increasing in the GVC intensity. Lastly, distributional effects of the reduction in trade costs are not monotonic in the GVC intensity. The effects on the skill premium are larger, when GVCs put larger weights on each country's comparative advantage stage and make the relative magnitude of the occupation intensity relevant.

4 Calibration

Our numerical exercise above shows the basic mechanism of our model in a simple 2-stage case with only 2 countries, 2 worker types, 2 occupations, and 2 production stages. We now calibrate the general version of our model to data. Our goal is to assess the role of GVCs as a propagation mechanism transmitting global integration shocks, such as China joining the WTO, to aggregate trade outcomes, as well as distributional outcomes, such as the skill premia. In particular, our focus is on the role of sectoral variation in the GVC intensity.

4.1 Countries, Worker Types, Occupations, and Production Stages

We calibrate the model for three countries–China, USA, and a constructed rest of the world (ROW).

Workers are classified by $T = 5$ types which are defined by educational attainment: 1) high school dropouts; 2) high school graduates; 3) workers with some college education; 4) college graduates; and 5) workers with advanced degrees. When we calculate the skill premium, we define skilled workers as those who have at least some college education. We define five occupation categories following Dorn (2009): 1) low-skilled service occupations and agricultural workers; 2) assemblers and machine operators; 3) precision production and crafts occupations; 4) administrative, clerical, and sales occupations; and 5) managers, professionals, and technicians. This categorization is based on both skill levels required by occupation and the routineness of occupation.

In addition we use the World Input-Output Database (WIOD) for 2000. We reduce the WIOD tables for that year into one with China, USA, and the rest-of-the-world, and with four sectors: agriculture, mining, manufacturing, and services. AG and de Gortari (2017) show how to map the GVC concepts into input-output flows. We will do this from our framework with two stages of production. In AG, the number of stages that fit their data the best is $J = 2$. Accordingly, we calibrate our model with two production stages, $J = 2$. [3]

4.2 Assigned Parameters or Exogenous Variables

We assign $\nu = 4$ from Simonovska and Waugh (2014) for the common stage-invariant part of trade elasticity. Conditional on the assigned value of ν, we calibrate bilateral trade

[3] In a more general version of calibration, J can be also jointly calibrated with other parameters of the model.

costs for each country pair and each sector using bilateral trade flows of final goods in the WIOD 2000. Type-level labor supply ($\bar{L}_{i,t}$) is obtained from Barro and Lee (2013), and the sector expenditure share b^s is calibrated to exactly match the expenditure share in the WIOD. We set $\sigma = 2$ for the elasticity of substitution between within-sector product varieties. Finally, we jointly calibrate the sector-specific GVC intensity γ^s, the value-added share α_i^s, Ricardian productivities A_i^s, and country- and stage-specific occupation intensity $\beta_i^{j,o}$. Details of calibration are discussed later in this section.

4.3 Calibration of Bilateral Trade Costs

Our model delivers a mapping from the GVC probability $\lambda_{l,n}^s$ to bilateral trade flows of goods. Similarly to AG, bilateral trade flows of final goods are simply defined by $\tilde{\lambda}_{in}^{F,s} = \sum_{l \in \Lambda_i^J} \lambda_{l,n}^s$, where Λ_i^J is a set of all GVC paths which perform the final production stage in country i. We obtain the data counterparts to these bilateral trade flows from the WIOD. In order to use $\tilde{\lambda}_{in}^{F,s}$ from the WIOD to calibrate bilateral trade costs, we impose two identifying assumptions. First, there is no trade cost for domestic transactions–i.e., $\tau_{ii}^s = 1$ for every i and s. Second, bilateral trade costs are symmetric–i.e., $\tau_{in}^s = \tau_{ni}^s$ for every (i, n) and s.

Using the expression of $\lambda_{l,n}^s$ from the model, the common trade elasticity, and these two identifying assumptions, we can back out bilateral trade costs ν by following the Head and Ries (2001) method:

$$\tau_{in}^s = [\frac{\tilde{\lambda}_{in}^{F,s}}{\tilde{\lambda}_{ii}^{F,s}} \frac{\tilde{\lambda}_{ni}^{F,s}}{\tilde{\lambda}_{nn}^{F,s}}]^{-\frac{1}{2\nu}}$$

We calibrate trade costs for the year 2000. Table 3 summarizes calibrated trade costs for each year. Not surprisingly, bilateral trade costs are lowest in the manufacturing sector and highest in the service sector. We will use the 2000 level of bilateral trade costs to calibrate other parameters of the model using the WIOD 2000.

Table 3: Calibrated τ_{in}^s

Country pair	Agriculture	Mining	Manufacturing	Service
China - USA	5.879	5.274	2.619	7.807
China - ROW	2.722	1.896	2.140	1.800
USA - ROW	3.002	3.671	2.864	3.017

4.4 Estimation of the Roy Parameters

We estimate the Roy parameters, $T_t^{s,o}$ and θ_t, using the US American Community Survey (ACS) for 2000. Workers draw sector- and occupation-specific idiosyncratic productivities from a Fréchet distribution $G_t^{s,o}(\epsilon)$ as defined in Section 2. Different worker types have different productivity distributions. The scale parameter $T_t^{s,o}$ governs the level of worker type t's average productivity for sector s and occupation o. The shape parameter θ_t is related to within-type heterogeneity of productivity. Using the independence assumption between productivity draws and the characteristics of Fréchet distribution, we can derive the distribution of the equilibrium observed wage $\tilde{w}$ for each worker type t[4]:

$$G_t^*(\tilde{w}) = \exp\{-[\sum_{s',o'} T_t^{s',o'}(w_i^{s',o'})^{\theta_t}]\tilde{w}^{-\theta_t}\}.$$

We use hourly wage profiles and individual's educational attainment in the US ACS 2000 data to estimate the parameters of $G_t^*(\tilde{w})$ for each worker type t. We jointly estimate $\sum_{s',o'} T_t^{s',o'}(w_{US}^{s',o'})^{\theta_t}$ and θ_t using the maximum likelihood.

Estimated $\sum_{s',o'} T_t^{s',o'}(w_{US}^{s',o'})^{\theta_t}$, labor allocation $\pi_{US,t}^{s,o}$ from the US ACS 2000, and the expression of $\pi_{US,t}^{s,o}$ from our model pin down individual $T_t^{s,o}$'s up to a normalization. Similarly to Hsieh et al. (2013), we normalize the scale parameter of high school dropouts, i.e., $T_1^{s,o} = 1$ for all (s,o). Then, we back out $T_t^{s,o}$ for $t \neq 1$. This normalization does not affect worker-level comparative advantage, because we compare ratios, not levels, of $T_t^{s,o}$ to shape worker-level comparative advantage.

Table 4 reports the estimates of θ_t and standard errors. The estimation result shows that better-educated workers have more dispersed productivity distributions within their types. Since θ_t is also the shape parameter of the distribution of equilibrium observed wages, this result also suggests that the wage distribution of high-skilled workers is more dispersed than that of low-skilled workers. This feature can be easily confirmed with individual wage profiles data.

Table 5 summarizes the estimates of $T_t^{s,o}$ for each type except for high school dropouts whose $T_t^{s,o}$'s are normalized to one. Worker-level comparative advantage is clearly identified across both sectors and occupations. While all worker types are more productive in absolute terms when they are in the service sector than in the agriculture sector, better-educated workers have a comparative advantage in the service sector. On the other hand, low-skilled workers have a comparative advantage in agriculture and mining sectors.

[4] The observed wage $\tilde{w}$ is different from per-unit wage $w_i^{s,o}$. Wages we observe in data are not $w_i^{s,o}$ but $\tilde{w}$ which takes both per-unit wage and worker productivity into account.

Table 4: ML Estimates of θ_t

	High School Dropouts	High School Graduates	Some College Education	College Graduates	Advanced Degrees
$\hat{\theta}_t$	1.972	1.862	1.735	1.603	1.480
S.E.	(0.0043)	(0.0055)	(0.0057)	(0.0015)	(0.0005)

Worker-level comparative advantage is much more clearly pronounced across occupations. While the average estimates of $T_t^{s,o}$ range from 0.898 to 2.466 across five occupations for high school graduates, the average $T_t^{s,o}$ of workers with advanced degrees for managerial and professional occupations is about 152 times larger than their average for low-skill service jobs. In other words, better educated workers have a much larger advantage for having high-skilled occupations than for being in the service sector. In addition, relative magnitudes of $T_t^{s,o}$ show that, for better educated workers, having high-skilled occupations is much more beneficial if they are in the service sector than in other sectors.

Table 5: Sector- and Occupation-level Averages of Estimated $T_t^{s,o}$

(a) Sector-level Average

	Agriculture	Mining	Manufacturing	Service
High school graduates	0.911	1.667	1.832	1.854
Some College Education	0.905	1.113	1.991	2.565
College Graduates	0.871	1.303	3.671	4.849
Advanced Degrees	0.773	0.703	2.715	5.911

(b) Occupation-level Average

	Low-skill Service Jobs	Assemblers Machine Operators	Precision Produc-tion Crafters	Admin Clerks Sales	Managers Prof Tech-nicians
High school graduates	0.898	0.839	1.316	2.311	2.466
Some College Education	0.471	0.344	0.938	2.231	4.235
College Graduates	0.180	0.118	0.439	1.599	11.030
Advanced Degrees	0.078	0.053	0.137	0.481	11.879

The estimated θ_t and $T_t^{s,o}$ shape worker-level comparative advantage within and across types, which is the Roy channel in our model. Since workers have different productivities not only across sectors but also occupations, the same sector-level trade shocks can generate different occupation-level responses among workers. We will show the trade-induced labor reallocation across sectors and occupations in our counterfactual exercises based on these estimated parameters. In addition, the relative magnitude of $T_t^{s,o}$ also affects country's endowment-based comparative advantage. The initial labor allocation pattern depends on the relative magnitude of $T_t^{s,o}$. Thus, together with the type-level labor supply $\bar{L}_{i,t}$, $T_t^{s,o}$ affects effective occupation-level labor endowment.

4.5 Calibration of the Production Parameters

After we pin down trade costs, the common trade elasticity, type-level labor supply, the Roy parameters, and the demand parameters, we calibrate the remaining production side parameters, γ^s, α_i^s, A_i^s, and $\beta_i^{j,o}$ for the year 2000. Calibration of the first three parameters follows AG by targeting similar sets of moments. Because our model has multiple sectors, we target sector-specific moments. Each set of targeted moments discussed below can be linked to each parameter. However, this relationship between targeted moments and parameters is not one-to-one. All of the calibrated parameters are jointly related to all of the targeted moments through the general equilibrium.

First, we match domestic absorptions of final goods and intermediate goods obtained from the WIOD 2000. The model expression for bilateral trade flows of final goods is $\tilde{\lambda}_{in}^{F,s}$ as derived above. Intermediate trade flows are from either the roundabout structure or from the GVC structure. We denote bilateral trade flows of intermediate goods from each structure by $\tilde{\lambda}_{ik}^{1,s}$ for the roundabout structure and $\tilde{\lambda}_{ik}^{2,s}$ for the GVC structure. The model expressions of these two variables are:

$$\tilde{\lambda}_{ik}^{1,s} = \tilde{\lambda}_{ik}^{F,s} b^s \sum_{s'} \frac{1-\alpha_k^{s'}}{\alpha_k^{s'}} \sum_o \sum_t \bar{w}_{k,t} \pi_{k,t}^{s',o} \bar{L}_{k,t}$$

$$\tilde{\lambda}_{ik}^{2,s} = \sum_{j=1}^{J-1} \tilde{\gamma}^{s,j} \sum_n \sum_{l \in \Lambda_{ik}^j} \lambda_{l,n}^s b^s [\sum_t \bar{w}_{n,t} \bar{L}_{n,t} + \sum_{s'} \frac{1-\alpha_n^{s'}}{\alpha_n^{s'}} \sum_o \sum_t \bar{w}_{n,t} \pi_{n,t}^{s',o} \bar{L}_{n,t}],$$

where $\Lambda_{ik}^j \equiv \{l = (l^1, \dots, l^J) \in \mathbf{N}^J | l^j = i \text{ and } l^{j+1} = k\}$ is a set of all GVC paths that cross country i at stage j and country k at stage $j+1$. Taking both roundabout and GVC production structure into account, bilateral trade flows of intermediate goods between country i and country k in our model are given by $\tilde{\lambda}_{ik}^{I,s} = \frac{\tilde{\lambda}_{ik}^{1,s}+\tilde{\lambda}_{ik}^{2,s}}{\sum_{i'}[\tilde{\lambda}_{i'k}^{1,s}+\tilde{\lambda}_{i'k}^{2,s}]}$. As in AG, diagonal entries of $\tilde{\lambda}_{in}^{F,s}$ and $\tilde{\lambda}_{ik}^{I,s}$ matrices help identify the GVC intensity γ^s. Unlike AG, we also exploit sector-level variation in domestic absorption to obtain the sector-specific GVC intensity.

The WIOD also reports value-added and gross output in each industry and each country. We aggregate them to three countries and four sectors. We then match the ratio of value-added to gross output in each sector and each country. This moment helps calibrate the country- and sector-specific value-added share α_i^s. We also target the share of GDP of each sector and each country in the total world GDP to calibrate the Ricardian productivity parameter A_i^s.

The occupation intensity $\beta_i^{j,o}$ at each production stage in each country is identified from a combination of diagonal entries of $\tilde{\lambda}_{in}^{F,s}$ and $\tilde{\lambda}_{ik}^{I,s}$ matrices, the share of value-added to gross output, and the share of wage payment to a certain occupation within each sector in each country. The last moment is obtained from the ILOSTAT database from the International Labor Organization (ILO.)

We jointly calibrate γ^s, α_i^s, A_i^s, and $\beta_i^{j,o}$ to match the model counterparts to the targeted moments most closely. Table A1 and Table A2 in the Appendix report the calibration results for γ^s, α_i^s, A_i^s, and $\beta_i^{j,o}$ for the year 2000. Calibrated parameters fit the targeted moments reasonably well. A linear correlation between targeted moments and model-generated moments is 0.8194. Our model fits diagonal entries of final and intermediate goods matrices and GDP shares best with correlation around 0.9.

The first calibration result is the large variation in γ^s across sectors. The range is 0.12 for agriculture to 0.5 for mining with manufacturing and services equal to 0.4 and 0.48, respectively. Contribution of stage 2 is higher in mining and service sectors with γ^s 0.50 and 0.48, respectively. This implies that more value-added is coming from stage 1 in agriculture and manufacturing sectors. Our calibration result shows that different sectors depend on upstream or downstream stages by a significantly different amount.

The calibrated value-added share α_i^s varies a great deal by country and sector. Calibrated values of our country- and sector-level parameters have a mean of 0.50 with a standard deviation of 0.22. Ricardian productivity A_i^s suggests that China has a comparative advantage in the manufacturing sector, and the US has a comparative advantage in the service sector. This Ricardian comparative advantage based on the relative magnitude of A_i^s will shape sector-wise specialization pattern, while the endowment-based comparative advantage will mainly determine stage-wise specialization pattern.

Calibration results for the occupation intensity $\beta_i^{j,o}$ show that a production stage in different countries has different interpretations in terms of occupation intensity. In relative terms, stage 1 uses high-skilled occupations more intensively in the US, but it uses less-skilled occupations more intensively in China. If US specializes in stage 1 and China specializes in stage 2 after trade liberalization, this pattern in $\beta_i^{j,o}$ will be consistent with the skill upgrading story of Feenstra and Hanson (1995), Zhu and Trefler (2005), and Costinot and Vogel (2010). However, in our model with an explicit vertical production structure, occupation intensities carry different weights based on the GVC intensity for each sector. In previous works about offshoring without vertical production structure, factor intensities essentially carry the same weight in the entire value chain. On the other hand, if we look into this story under the GVC context, our calibration of γ^s shows that the condition of the same weight is not satisfied. In other words, the role of occupation intensity is more or less important across stages and sectors depending on the magnitude of γ^s. We will further discuss this mechanism in the next section.

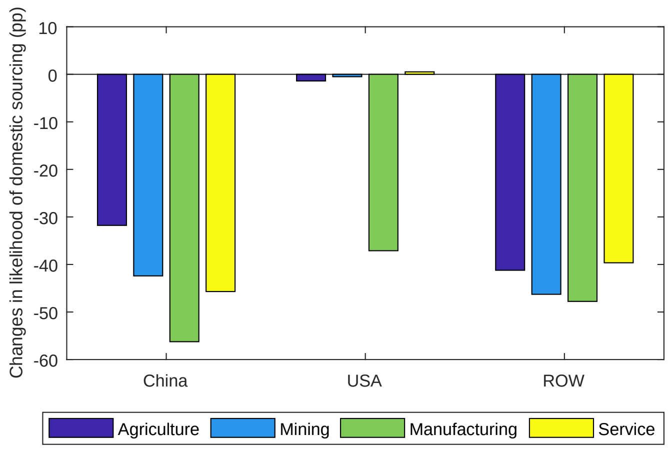
5 Counterfactuals

Based on the calibrated and estimated parameters from Section 4, we perform counterfactual exercises in order to quantitatively assess the aggregate and distributional impacts of trade liberalization. We solve the model with bilateral trade costs and other model parameters calibrated to the year 2000. We then introduce exogenous changes in bilateral trade costs to the model. The main counterfactual scenario we look at is a 50% decline in trade costs for China-USA and China-ROW. The goal of this counterfactual is to quantitatively assess the aggregate and distributional effects of China's integration into world economy in an explicit GVC setting.

This is especially relevant for China, because since it joined the WTO in 2001, it has caused a major upheaval to the global economy, and because it has heavily specialized in global value chains. Hence, our model, which features both sector-level and stage-level specialization, and in which country-level comparative advantage interacts with worker-level comparative advantage and the relative GVC intensity across sectors, should capture the multiple facets in which the China shock affects labor demand and labor supply in different countries.

We first show the aggregate impacts of the China trade integration shock. Figure 5 shows counterfactual changes in the prevalence of domestic sourcing $\lambda^s_{(i,i),i}$. Countries are less likely to source both production stages from domestic producers, when trade costs with China go down. The manufacturing sector shows larger declines of the likelihood of domestic sourcing in all countries, ranging from -37.11% to -56.24%. This result is related to the fact that China has a comparative advantage in the manufacturing sector and also to the higher GVC intensity–lower γ^s–in the manufacturing sector. Magnification of aggregate outcomes in response to decline in trade costs is larger in the sector with a higher GVC intensity. The aggregate effective trade elasticity is higher, the more the sector depends on the GVC.

Figure 5: Counterfactual Changes in the Prevalence of Domestic Sourcing $\lambda^s_{(i,i),i}$



The counterfactual also implies that the likelihood of domestic sourcing in the service sector increases slightly–0.52%–in the US. This result can be understood based on sector- and stage-level specialization patterns. Sector-level specialization patterns follow the Ricardian productivity A^s_i as calibrated in the previous section. China specializes in the manufacturing and agriculture sectors, and the US specializes in the service sector. A strong comparative advantage that the US has for the service sector expands both stage 1 and stage 2 demands of the service sector, which makes it more likely for the US to source both stages domestically.

Given this specialization pattern, Table 6 shows the stage-level specialization pattern in response to a decline in trade costs with China in more details. This table shows for each country-sector pair the percentage change in stage 1 output as a share of both stage 1 and stage 2 output. When trade costs with China decrease, China specializes in stage 2 in all sectors and the US specializes in stage 1 in all sectors, but agriculture. A smaller increase in the stage 1 output share in the US service sector (compared to other sectors) is related to the increase in domestic sourcing in Figure 5 owing to their strong sector-level comparative advantage in services. The US comparative advantage in the service sector in fact dominates its comparative advantage in stage 1, which makes it more likely to source both stages of the service sector from itself, as shown in Figure 5.

Table 6: Counterfactual Changes in the Share of Stage 1 within Sectors (%)

	Agriculture	Mining	Manufacturing	Service
China	-10.882	-94.313	-57.366	-91.365
USA	-4.968	13.677	19.517	2.169
ROW	-43.780	15.794	-8.555	19.862

Based on the stage-level specialization pattern and the calibrated occupation intensities $\beta_i^{j,o}$, the decline in trade costs may increase the skill premium in both China and the US if all stages are important for the total value chain. In other words, if γ^s is the same across all sectors and its value is not extreme, the skill upgrading story in which offshoring may increase the skill premium in both North and South holds in our GVC setting. However, the magnitude should depend on the GVC intensity, because our calibration results for γ^s show that in fact, sectors differ in GVC intensity. Therefore, whether the skill upgrading story holds under the context of GVC depends on how much each sector depends on GVCs.

Our measure of the skill premium is the wage premium of workers who have at least some college education over workers without any college education. The model counterpart of the skill premium is $\bar{w}_{i,H}/\bar{w}_{i,L}$, where worker types H and L are defined in the same way. In this counterfactual exercise, our model predicts that decline of trade costs with China would increase the skill premium in all three countries, China, USA, and ROW, by 0.246%, 0.936%, and 1.094%, respectively. In terms of the direction of changes in the skill premium, the result for the US is straightforward. The US has a comparative advantage in the service sector and in stage 1 where high-skilled occupations are used more intensively. In addition, as our estimates of $T_t^{s,o}$ show, better educated workers have a comparative advantage in the service sector and in high-skilled occupations. Furthermore, having a high-skilled occupation is much more beneficial for better educated workers when they are in the service sector. The share of contribution from their comparative advantage stage, $1-\gamma^s$, is not extreme in any sector. Therefore, the fact that stage 1 uses high-skilled occupations more intensively is relevant and thus shifts up the labor demand for better educated workers.

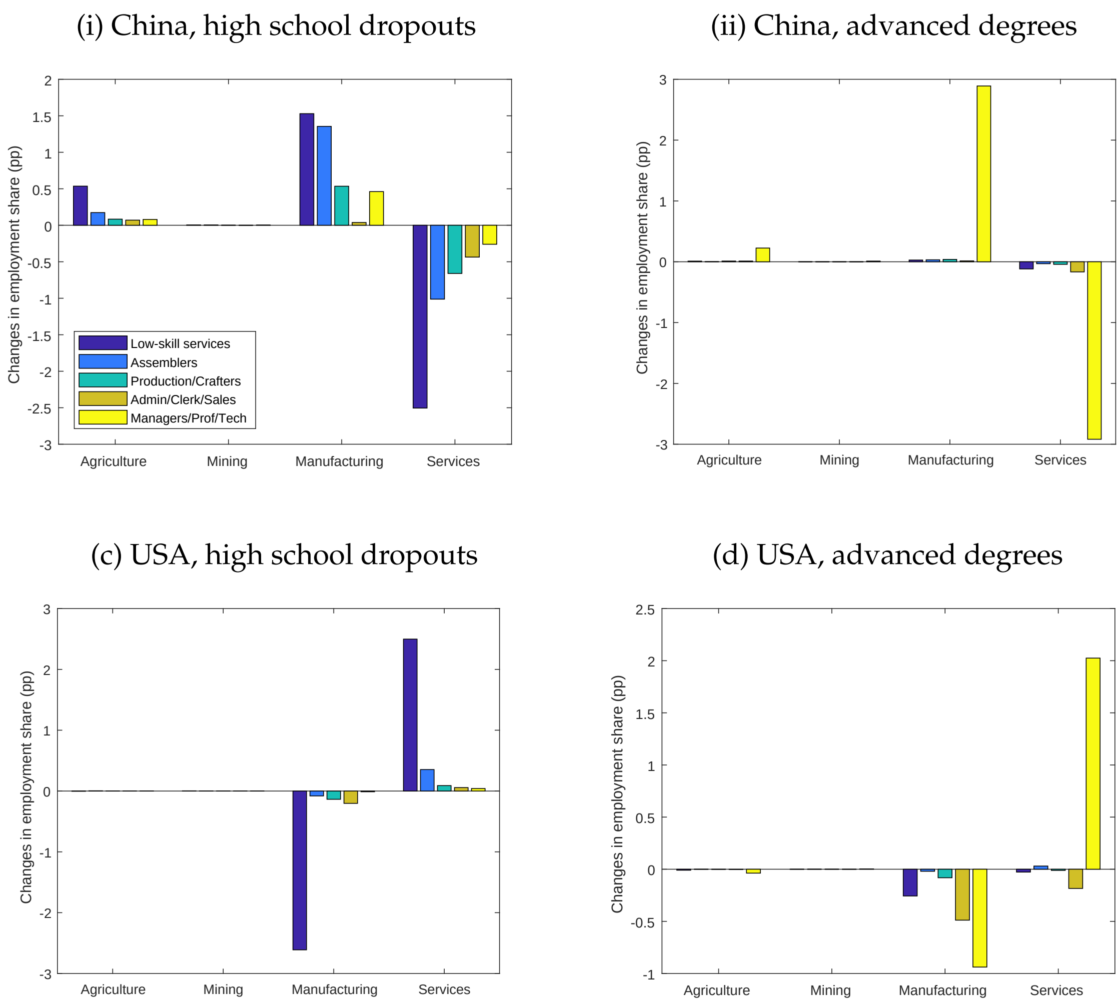
The increase in the skill premium in China can be also explained based on the occupation intensity and the Roy mechanism. China specializes in stage 2 which is relatively more high-skilled-occupation-intensive from China's perspective. Combined with worker-level comparative advantage as in the US, labor demand for better educated workers should increase also in China. This result is consistent with the previously mentioned skill upgrading story in the literature.

In terms of the magnitude of increases, our GVC structure provides additional explanation. Since γ^s is relatively small in the manufacturing sector in which China has a comparative advantage, the fact that stage 2 uses high-skilled occupations more intensively does not drive up the labor demand for better educated workers as much as models without vertical production structure would. This limits the increase of the skill premium in China. Similarly, US has a comparative advantage in stage 1 and in the service sector. However, compared to agriculture and manufacturing sectors, the service sector is where stage 1 has relatively lower weights. Therefore, the increase of the skill premium is limited in magnitude in the US, as well.

Combining our calibration results with the counterfactual result, we conclude that the GVC intensity is a magnifying factor for the aggregate effects of trade shocks, but a smoothing factor for distributional effects. A sector that depends more on GVCs has a larger effective trade elasticity overall, thus it responds more to trade shocks. On the other hand, calibrated values of the GVC intensity show that there is lower intensity, or weight, on each country's comparative advantage stage and sector combination. This limits the magnitude of increases in the skill premium for both countries. If γ^s puts larger weight on each country's comparative advantage sector and stage combination, GVC may magnify the trade-induced increase of the skill premium.

Our model also shows labor reallocation patterns within each worker type in response to the China trade integration shock. Figure 6 shows the counterfactual labor reallocation across sectors and occupations for high school dropouts and workers with advanced degrees in US and China. Country's comparative advantage across sectors is a major factor that determines worker's reallocation across sectors. In the US, both worker types are likely to move to the service sector. In China, on the other hand, both types tend to reallocate into the manufacturing sector. While sector-level reallocation is similar between worker types, different worker types tend to choose different occupations even when they are moving into the same sector. This occupation-level labor reallocation is determined by worker-level comparative advantage shaped based on the relative magnitude of $T_t^{s,o}$ estimates. For example, in the US, even though both worker types are likely to move into the service sector, low-skilled workers are going there for low-skill service occupations, while better educated workers are much more likely to have managerial and professional occupations in the service sector. Lastly, our model predicts more reallocation within less educated worker types, which is related to their larger labor allocation elasticity θ_t from our estimation.

Figure 6: Within-worker-type Reallocation of Labor



Alternative Counterfactuals with Different GVC Intensities In order to investigate the role of the weight that GVC intensities impose on distributional impacts of the China shock, we re-calibrate the model with alternative values of GVC intensities. We keep the values of the occupation intensity $\beta_i^{j,o}$ from our baseline calibration and set $\gamma^s = 1$ for the manufacturing sector and $\gamma^s = 0$ for the service sector. This specification puts extreme weights on each country's comparative advantage sector and stage. We set $\gamma^s = 0.5$ for the remaining two sectors, so that both stages are equally important in those sectors. We then re-calibrate the Ricardian productivity A_i^s and the value-added share α_i^s given those parameter values.

The counterfactual scenario is the same: 50% declines in bilateral trade costs with China. Counterfactual changes in the skill premium in response to this China shock with the re-calibrated parameters remain the same in terms of signs. While the skill premium increases in both China and the US, the magnitude of increases almost doubled for both countries–0.582% increase in China and 1.468% increase for the US–with this alternative specification, compared to our baseline counterfactual results. This result suggests that if GVC intensities in fact put larger weights on each country's comparative advantage sector and stage, then changes in labor demand based on the relative occupation intensity will be larger. China specializes in stage 2 and manufacturing, and all value-added in the manufacturing sector comes from stage 2 with an alternative value $\gamma^s = 1$ for manufacturing. As a result, the fact that stage 2 in China is relatively intensive in high-skilled-occupations carries the maximum weight. A similar mechanism is operative for the US, stage 1 and services, and an alternative value $\gamma^s = 0$ for services. This result is in line with our simulation of the simple 2^5 case. In the simulation, when we put larger weights on each country's comparative advantage sector and stage by varying the gap between γ^s across two sectors, the effect of decline in trade costs on the skill premium becomes larger.

In summary, our calibration and counterfactual exercises show that the China shock increases the skill premium in both China and US through GVCs by having both countries specialize in sector and stage where they use high-skilled-occupations more intensively. Sectors depend more on stage 1, e.g., manufacturing, have larger aggregate effects from the China shock. On the other hand, our results indicate that GVCs make distributional effects of trade liberalization smaller in both countries by putting smaller weights on each country's comparative advantage sector and stage.

6 Conclusion

[To be added]

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A Tables and Figures

Table A1: Calibrated γ^s, α_i^s, and A_i^s for the Year 2000

(a) GVC Intensity, γ^s

	Agriculture	Mining	Manufacturing	Service
γ^s	0.1213	0.5007	0.3999	0.4475

(b) Roundabout Intensity, α_i^s

	Agriculture	Mining	Manufacturing	Service
China	0.2893	0.5140	0.3747	0.5405
USA	0.2347	0.2788	0.3847	0.4668
ROW	1	0.8272	0.5900	0.5001

(c) Ricardian Productivity, A_i^s

	Agriculture	Mining	Manufacturing	Service
China	36.748	66.968	94.982	63.733
USA	44.031	52	51.938	162.62
ROW	74.875	150.38	199.97	100

Table A2: Calibrated $\beta_i^{j,o}$ for the Year 2000

(a) China

	Low-skill Service Jobs	Assemblers Machine Operators	Precision Production Crafters	Admin Clerks Sales	Managers Professionals Technicians
Stage 1	0.4271	0.1391	0.1390	0.1549	0.1389
Stage 2	0.2969	0.2871	0.1250	3.27E-17	0.2900

(b) USA

	Low-skill Service Jobs	Assemblers Machine Operators	Precision Production Crafters	Admin Clerks Sales	Managers Professionals Technicians
Stage 1	0.5581	0.0703	0.0351	0.0505	0.2851
Stage 2	0.6250	1.53E-06	0.0625	0.3130	1.53E-06

(c) ROW

	Low-skill Service Jobs	Assemblers Machine Operators	Precision Production Crafters	Admin Clerks Sales	Managers Professionals Technicians
Stage 1	0.8398	1.53E-06	1.53E-06	0.1602	1.53E-06
Stage 2	5.55E-17	0.2788	0.1332	1.91E-04	0.5889