Global Value Chains

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Online Appendix (Not for Publication)

A Modeling GVCs: Macro Approaches

A.1 Some Details of The Caliendo-Parro Model in Section 4.1

A.1.1 Equilibrium of the Model (Unabridged)

Consider the decision problem of either the representative consumer or a firm in country j, regarding which country to purchase variety ω^s from. As in Eaton and Kortum (2002), this corresponds to choosing the lowest-cost source country across $i \in \{1, \ldots, J\}$, after factoring in the unit production costs c_i^s and iceberg trade costs τ_{ij}^s across all potential source countries i.[1] The solution to this discrete choice problem yields an expression for the expenditure share of country j spent on industry-s varieties (intermediate or final goods) that come from country i:

$$\pi_{ij}^s = \frac{T_i^s (c_i^s \tau_{ij}^s)^{-\theta^s}}{\sum_{k=1}^J T_k^s (c_k^s \tau_{kj}^s)^{-\theta^s}}. \tag{A.1}$$

Country j's spending on country-i, industry-s's output is higher the higher the state of technology T_i^s, the lower the bundle cost c_i^s, and the lower the trade costs τ_{ij}^s associated with the i-s pair when selling in j. The unit production cost c_j^s is in turn obtained as the solution to the cost-minimization problem faced by each industry-s firm in country j, based on the production function (7). This is given by:

$$c_j^s = \Upsilon_j^s w_j^{1-\sum_{r=1}^S \gamma_j^{rs}} \prod_{r=1}^S \left(P_j^r\right)^{\gamma_j^{rs}}, \tag{A.2}$$

where Υ_j^s is a constant that depends only on the parameters γ_j^{rs}, and P_j^r is the ideal price index of the industry-r composite being used as an intermediate input in country j. Following Eaton and

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[1] We ignore tariffs and their implied tariff revenue, but they are modeled and taken into account in Caliendo and Parro (2015).

Kortum (2002), the expression for P_j^r is given explicitly by:

$$P_j^r = \kappa^r \left[\sum_{i=1}^{J} T_i^r \left(c_i^r \tau_{ij}^r \right)^{-\theta^r} \right]^{-1/\theta^r}, \tag{A.3}$$

where κ^r is a constant that depends only on σ^r and θ^r.[2]

Let X_{ij}^s denote the expenditure of country j on industry-s varieties from country i. This is the sum of country-j expenditures on the industry-s composite from country i, over both its use as an intermediate input and for final consumption. In turn, define: (i) $X_j^s = \sum_{i=1}^{J} X_{ij}^s$ as the total expenditure of country j on industry-s varieties; and (ii) Y_j^s as the value of gross output in industry s produced in country j. Having defined these objects, we can close the model by clearing the market for each industry in each country:

$$X_j^s = \sum_{r=1}^{S} \gamma_j^{sr} \underbrace{\sum_{i=1}^{J} X_i^r \pi_{ji}^r}_{Y_j^r} + \alpha_j^s \left(w_j L_j + D_j \right). \tag{A.4}$$

Note that the first term on the right-hand side of (A.4) is equal to the total purchases of intermediate inputs from industry s, where the sum is taken over all industries r that purchase intermediate inputs from s.[3] D_j is the national deficit of country j, computed as the sum of all sectoral and final-use imports of a country minus the sectoral and final-use outputs. Then, the second term on the right-hand side is the total purchases by country j on industry s for final consumption.

We finally impose trade balance, equating a country j's imports to its exports plus its observed deficit D_j:

$$\sum_{s=1}^{S} X_j^s = \sum_{s=1}^{S} \sum_{i=1}^{J} X_j^s \pi_{ij}^s = \sum_{s=1}^{S} \sum_{i=1}^{J} X_i^s \pi_{ji}^s + D_j \tag{A.5}$$

One can show that this last equilibrium condition can alternatively be derived from the equality of (equipped) labor income and total value added.[4] The equilibrium of the model is then pinned down by the system of equations: (A.1), (A.2), (A.3), (A.4), and (A.5).[5]

[2] We assume that $\sigma^r < 1 + \theta^r$ for each r, in order for the ideal price index over this industry-r CES aggregate to be well-defined.

[3] The manipulation uses the fact that gross output of industry r in country j is equal to the world's total purchases from this country-industry.

[4] Aggregating (A.4) across sectors, and using (A.5), one obtains after some manipulations:

$$w_j L_j = \sum_{r=1}^{S} \left(1 - \sum_{s=1}^{S} \gamma_j^{sr} \right) \sum_{i=1}^{J} \pi_{ji}^r X_i^r = \sum_{r=1}^{S} \left(1 - \sum_{s=1}^{S} \gamma_j^{sr} \right) Y_j^r.$$

In words, the total wage payments to labor in country j are equal to total value added across all sectors of j.

[5] Note that (A.1) comprises $J \times (J-1) \times S$ independent equations, since the shares π_{ij}^s need to sum to 1 for each j-s pair. Also, (A.2) and (A.3) each comprise $J \times S$ equations. The market clearing condition (A.4) comprises $J \times S - 1$ independent equations, since one of these is redundant by Walras' Law. Finally, there are J trade balance conditions in (A.5). On the other hand, the equilibrium seeks to solve for the following objects: the shares π_{ij}^s (of which there are $J \times (J-1) \times S$ independent shares), the unit production costs c_j^s and price indices P_j^s (of which there are $J \times S$ each), as well as the $J - 1$ wage levels w_j's (with one country's wage chosen as the numéraire) and the

A.1.2 The Hat-Algebra Equations

We denote the counterfactual value of a parameter or variable x with a prime (e.g., x') and use hats to denote the relative change in these variables, i.e., $\hat{x} = x'/x$. In practice, we will follow Caliendo and Parro (2015) in focusing on the effects of changes in trade costs τ_{ij}^s, though one could also use this approach to explore changes in the preference parameters α_j^s, or in the technology parameters T_i^r. For simplicity, assume that deficits D_j are held constant in the counterfactuals one studies.

Consider first the effects of trade cost shocks on trade shares. Using the hat algebra notation, it is easy to verify that (A.1) can be re-written:

$$\hat{\pi}_{ij}^r = \left(\frac{\hat{c}_i^r \hat{\tau}_{ij}^r}{\hat{P}_j^r} \right)^{-\theta^r} . \tag{A.6}$$

In words, the percentage response of trade shares is purely shaped by the trade elasticity parameters θ^r and by the percentage shifts of the various trade cost parameters, as well as the percentage responses of the unit costs c_i^r, and the price index P_j^r. It is worth stressing that (A.6) is *not* an approximation: it holds exactly for any shock to trade costs, regardless of the size of the shock. Notice also that the *level* of trade costs or the unobserved technological parameters T_i^r do not appear directly in these equations (though in some cases, it may be necessary to have knowledge of the initial level of trade costs to calibrate the relevant percentage change $\hat{\tau}_{ij}^r$ in these costs).

The responses of the unit costs c_i^r and the price index P_j^r to changes in the environment can be obtained from simple manipulations of equations (A.2) and (A.3). More specifically, plugging in the expressions for the trade shares from (A.1), we obtain:

$$\hat{c}_j^s = (\hat{w}_j)^{1-\sum_{r=1}^{S} \gamma_j^{rs}} \prod_{r=1}^{S} \left(\hat{P}_j^r \right)^{\gamma_j^{rs}} , \tag{A.7}$$

and:

$$\hat{P}_j^r = \left[\sum_{i=1}^{J} \pi_{ij}^r \left(\hat{c}_i^r \hat{\tau}_{ij}^r \right)^{-\theta^r} \right]^{-1/\theta^r} . \tag{A.8}$$

There are two key features of these two sets of equations. First, the only variables in levels that appear in these equations are the trade shares prior to the shocks (which are observable), the Cobb-Douglas technological parameters γ_j^{rs} (which are retrievable from the data in a WIOT), and the trade elasticity parameters θ^r.[6] Second, it is clear from inspection that combining (A.7) and (A.8), one should be able to solve numerically for $\hat{c}_j^s$ and $\hat{P}_j^r$ as a function of these initial trade shares, as well as the percentage changes in wages ($\hat{w}_j$) and input trade costs ($\hat{\tau}_{ij}^r$). Plugging these resulting values of $\hat{c}_j^s$ and $\hat{P}_j^r$ into (A.6), this then allows us to express the changes in trade shares

$J \times S$ expenditure levels X_j^s's. Thus, we have as many equilibrium conditions as variables to be solved for.

[6] Specifically, if the model is not misspecified, γ_j^{rs} can be obtained by computing $\gamma_j^{rs} = \sum_{i=1}^{J} Z_{ij}^{rs} / Y_j^s$ for each country j and each pair of industries r-s. Similarly, the Cobb-Douglas consumer spending shares α_j^s, which will appear in expression (A.9) below, can be obtained as $\alpha_j^s = \sum_{i=1}^{J} F_{ij}^s / (w_j L_j + D_j)$.

as a function of "observables" (π_{ij}^s and γ_j^{rs}), the trade elasticity parameters θ^s, and the percentage changes in wages and trade costs.

We finally discuss how to trace the response of wages, as well as gross output and value added, to the shocks. For that, we invoke the goods-market clearing conditions (A.4) and the trade balance conditions (A.5). In the counterfactual equilibrium, these can be re-written as:

$$\left(X_j^s\right)' = \sum_{r=1}^{S} \gamma_j^{sr} \sum_{i=1}^{J} \left(\pi_{ji}^r\right)' \left(X_i^r\right)' + \alpha_j^s \left(\hat{w}_j w_j L_j + D_j\right) \tag{A.9}$$

and:

$$\sum_{s=1}^{S} \left(X_j^s\right)' = \sum_{s=1}^{S} \sum_{i=1}^{J} \left(\pi_{ji}^s\right)' \left(X_i^s\right)' + D_j. \tag{A.10}$$

Noting that $\left(\pi_{ij}^r\right)' = \hat{\pi}_{ij}^r \cdot \pi_{ij}^r$, this system of equations delivers solutions for $\left(X_j^s\right)'$ and $\hat{w}_j$ as a function of changes in trade costs, observable pre-shock trade shares, and Cobb-Douglas parameters (as well as the elasticities).

In sum, equations (A.6)-(A.10) demonstrate that in order to compute counterfactuals that shock trade costs while holding all other parameters constant, all that is required is the initial values of a set of variables that are easily retrieved from a WIOT, as well as values for the trade elasticities θ^s.

A.1.3 Applications of the Caliendo-Parro Model

Several authors have used the Caliendo and Parro (2015) framework to quantify the effects of trade wars, and more specifically, of the recent U.S-China trade tensions (see, among others, Caceres et al., 2019; Beshkar and Lashkaripour, 2020; Ju et al., 2020; Charbonneau and Landry, 2018; Wicht, 2019). Another salient application is Dhingra et al. (2017)'s analysis of the aggregate income implications of the U.K.'s exit from the European Union (or Brexit). Other authors have employed the Caliendo-Parro framework to study the consequences of specific preferential trade agreements, such as the Transatlantic Trade and Investment Partnership (Aichele et al., 2016), or the U.S.-Japan Free Trade Agreement of 2019 (Walter, 2018). Furthermore, the framework has been employed to assess the economic consequences of China's Belt and Road Initiative (De Soyres et al., 2018), and to quantify the welfare implications for Japan of productivity growth in emerging economies during the period 1995-2007 (Furusawa and Sugita, 2020). A more recent wave of work has employed the framework (or slight variants of it) to study the economic consequences of the ongoing COVID-19 pandemic, largely interpreting the shock as a labor supply shock (see Bonadio et al., 2020; Sforza and Steininger, 2020; Eppinger et al., 2020).

A.2 Some Details of the Multi-Stage Model in Section 4.2

A.2.1 Equilibrium with Multiple Stages

The bulk of "macro" quantitative work on GVCs has focused on models of the type developed in Section 4.2 with only two stages. There are various reasons for this focus (more on this below), but one of them is that in the absence of a tractable framework to pin down the relative prevalence of various GVCs, estimating models with more than two stages is highly complex. One of the advantages of the formulation of technology in Antràs and de Gortari (2020) is that their equilibrium equations naturally extend to an environment with an arbitrary number of stages N. More specifically, by specifying a Fréchet distribution of productivity at the chain level, or by making suitable assumptions about incomplete information regarding upstream suppliers, Antràs and de Gortari (2020) find that the share of country j's spending on final goods produced under a particular GVC path $\boldsymbol{\ell} = \{\ell(1), \ell(2), \ldots, \ell(N)\} \in \mathcal{J}^N$ is given by:

$$\pi_{\boldsymbol{\ell}j} = \frac{\prod_{n=1}^{N-1}\left(\left(T^n_{\ell(n)}\right)^{\alpha_n}\left(\left(w_{\ell(n)}\right)^{\alpha_n}\tau_{\ell(n)\ell(n+1)}\right)^{-\theta}\right)^{\beta_n} \times \left(T^N_{\ell(N)}\right)^{\alpha_N}\left(\left(w_{\ell(N)}\right)^{\alpha_N}\tau_{\ell(N)j}\right)^{-\theta}}{\sum_{\boldsymbol{\ell}\in\mathcal{J}^N}\prod_{n=1}^{N-1}\left(\left(T^n_{\ell(n)}\right)^{\alpha_n}\left(\left(w_{\ell(n)}\right)^{\alpha_n}\tau_{\ell(n)\ell(n+1)}\right)^{-\theta}\right)^{\beta_n} \times \left(T^N_{\ell(N)}\right)^{\alpha_N}\left(\left(w_{\ell(N)}\right)^{\alpha_N}\tau_{\ell(N)j}\right)^{-\theta}}, \tag{A.11}$$

where α_n continues to denote the labor share in stage n, and where β_n is defined as $\beta_n \equiv \prod_{m=n+1}^{N}(1-\alpha_m)$. Notice that GVC shares continue to feature a magnified effect of trade costs as well as an increasing trade-cost elasticity as one moves to more and more downstream stages (since β_n is increasing in n). The price index P_j in country j is again a simple power function of the denominator in (A.11) or:

$$P_j = \kappa\left(\sum_{\boldsymbol{\ell}\in\mathcal{J}^N}\prod_{n=1}^{N-1}\left(\left(T^n_{\ell(n)}\right)^{\alpha_n}\left(\left(w_{\ell(n)}\right)^{\alpha_n}\tau_{\ell(n)\ell(n+1)}\right)^{-\theta}\right)^{\beta_n} \times \left(T^N_{\ell(N)}\right)^{\alpha_N}\left(\left(w_{\ell(N)}\right)^{\alpha_N}\tau_{\ell(N)j}\right)^{-\theta}\right)^{-1/\theta}, \tag{A.12}$$

where κ is a constant that depends only on σ and θ.[7]

To solve for equilibrium wages, notice that for all GVCs, stage-n value added (or labor income) accounts for a share $\alpha_n\beta_n$ of the value of the finished good emanating from that GVC. Furthermore, total spending in any country j is given by w_jL_j, and the share of that spending by j going to GVCs in which country i is in position n is given by $\Pr(\Lambda^n_i, j) = \sum_{\boldsymbol{\ell}\in\Lambda^n_i}\pi_{\boldsymbol{\ell}j}$, where $\Lambda^n_i = \left\{\boldsymbol{\ell}\in\mathcal{J}^N \mid \ell(n) = i\right\}$ and $\pi_{\boldsymbol{\ell}j}$ is given in equation (A.11). It thus follows that the equilibrium wage vector is determined by the solution of the following system of equations:

$$w_iL_i = \sum_{j\in\mathcal{J}}\sum_{n\in\mathcal{N}}\alpha_n\beta_n \times \Pr(\Lambda^n_i, j) \times w_jL_j. \tag{A.13}$$

The system of equations is nonlinear because $\Pr(\Lambda^n_i, j)$ is a nonlinear function of wages themselves, and of the vector $\boldsymbol{P}$ of ideal price indices, which is in turn a function of the vector of wages $\boldsymbol{w}$. When $N = 1$, we have that $\alpha_N\beta_N = 1$ and $\Pr(\Lambda^n_i, j) = \pi_{ij} = (\tau_{ij}c_i)^{-\theta}T^1_i / \sum_k(\tau_{kj}c_k)^{-\theta}T^1_k$. The equilibrium then reduces to the general equilibrium in Eaton and Kortum (2002). Antràs and de Gortari (2020) derive a set of sufficient conditions that ensure that this solution exists and is

[7] For the price index to be well-defined, one needs to impose $\sigma - 1 < \theta$.

unique for an arbitrary number of stages N.

Although the equilibrium is thus straightforward to compute, it is worth pointing out that with J country and N stages, there will be J^N active value chains for each destination country j. Hence, although the model can we analyzed for an arbitrary number of stages, in empirical applications, computational constraints are still likely to constrain how large N (or J) can be. We return to related computational constraints in Section 5 of the main text.

A.2.2 Extensions and Mapping to Data

A first straightforward extension is to allow production at each stage to use both "equipped labor" as well as a bundle of intermediates or materials. Following Eaton and Kortum (2002), assume that this bundle is the same CES aggregator as in preferences. In other words, part of final-good production is not absorbed by consumers, but rather by firms that use those goods as a bundle of materials. Letting the cost c_i of the composite factor in country i be captured by a Cobb-Douglas aggregator, we have $c_i = (w_i)^{\gamma} (P_i)^{1-\gamma}$, where P_i is the ideal price index associated with preferences. As shown by Antràs and de Gortari (2020), all equilibrium equations – (A.11) through (A.13) – continue to hold with minor modifications, and the same is true about expression (15) in the main text for the gains from trade. Furthermore, when $N = 1$ the model reduces exactly to the Eaton and Kortum (2002) model.

How does one map this strict multi-stage generalization of the Eaton and Kortum (2002) model to the data? Although the "GVC trade shares" in (A.11) are not observable in the data, it is straightforward to manipulate them to obtain closed-form expressions for various entries of a WIOT (when the data is collapsed into a single sector). Let us illustrate this for the case of the final-use vector. Notice that for final goods to flow from a given source country i to a given destination country j, it must be the case that country i is in position N in a chain serving consumers in country j. Defining the set of GVCs flowing through i at position n by $\Lambda_i^n \in \mathcal{J}^{N-1}$, the overall share of spending in country j on goods assembled in country i (i.e., in GVCs in which country i produces stage N) can be expressed as:

$$\pi_{ij}^F = \frac{\sum_{\ell \in \Lambda_i^N} \prod_{n=1}^{N-1} \left(\left(T_{\ell(n)}^n \right)^{\alpha_n} \left(\left(c_{\ell(n)} \right)^{\alpha_n} \tau_{\ell(n)\ell(n+1)} \right)^{-\theta} \right)^{\beta_n} \times \left(T_i^N \right)^{\alpha_N} \left((c_i)^{\alpha_N} \tau_{ij} \right)^{-\theta}}{\Theta_j}, \tag{A.14}$$

where Θ_j is the denominator in equation (A.11). It then follows that final-good trade flows between any two countries i and j are then simply given by $\pi_{ij}^F \times w_j L_j$ (trade imbalances are ignored here but would be straightforward to incorporate). Computing intermediate input flows based on the "GVC trade shares" in (A.11) is a bit more tedious, since one needs to take into account both vertical trade between two contiguous stages, but also intermediate input trade flows associated with the use of the bundle of inputs at each stage. Yet, as Antràs and de Gortari (2020) show, it is straightforward to obtain closed-form expressions for intermediate-input trade flows between any two countries i and j. With these expressions at hand, it then becomes feasible to estimate the key parameters of the model via maximum likelihood by minimizing the distance between various moments of a WIOT and their model counterparts.

The above framework can also be easily extended to a multi-industry environment that nests the Caliendo and Parro (2015) model. To see this, assume there are S industries indexed by $s \in \mathcal{S}$, with preferences given in (6) in the main text, with sector-specific Fréchet parameters θ^s, and with the cost of the bundle of labor and inputs used by country j in sector s given by:

$$c_j^s = \Upsilon_j^s w_j^{1-\sum_{r=1}^{S} \gamma_j^{rs}} \prod_{r=1}^{S} \left(P_j^r\right)^{\gamma_i^{rs}},$$

as in equation (10) in the main text. In such a case, letting $N = 1$, all equilibrium equations reduce exactly to the roundabout model of GVCs in Caliendo and Parro (2015). As shown in Antràs and de Gortari (2020) and de Gortari (2019), it is also straightforward to develop extensions of the framework that add multiple stages to certain variants of the Caliendo and Parro (2015) framework, such as those in Alexander (2017) and Antràs and Chor (2019), which allow certain parameters to be a function not just of the identity of the producing country-industry pair, but also of the consuming country-industry pair.[8] A different matter is the ease with which these multi-industry extensions can be taken to the data, an issue we will address shortly.

B Modeling GVCs: Micro Approaches

B.1 Selection into Forward GVC Participation

B.1.1 Equilibrium with Nontradable Final Goods

We provide here the details of the equilibrium for the case in which final goods are prohibitively costly to trade across countries ($\tau_{ij}^F \to \infty$). Consider the decisions of final-good producers in a given country j. Invoking constant-markup pricing, it is easy to verify that their profits are given by:

$$\pi_j^F = \left(z_j^F\right)^{\sigma-1} \left((w_j)^{\gamma} \left(P_j^I\right)^{1-\gamma}\right)^{-(\sigma-1)} B_j^F - w_j f_j^F, \tag{B.1}$$

where $B_j^F = \frac{1}{\sigma}\left(\frac{\sigma}{\sigma-1}\right)^{1-\sigma} w_j L_j P_j^{\sigma-1}$, and where we have imposed that, given free entry in both the downstream and upstream sectors, all income in all economies is labor income. Given the definition of the price index, and the fact that firms are homogeneous, we obtain a simple expression for the measure of active final-good producers in country j:

$$N_j^F = \frac{L_j}{\sigma f_j^F}.$$

Note that each of these N_j^F producers will allocate a share $1-\gamma$ of their operating costs to purchasing

[8] de Gortari (2019) interprets these more flexible versions of the model as capturing specialized or customized inputs along GVCs.

intermediate inputs. Because unit costs are a constant multiple of operating profits, and the latter are brought down to $w_j f_j^F$ by free entry, we can conclude that intermediate input demand in country j is given by:

$$P_j^I \mathcal{M}_j = N_j^F \times (\sigma - 1)(1-\gamma) \times w_j f_j^F = \frac{\sigma - 1}{\sigma}(1-\gamma) w_j L_j,$$

and is thus a simple multiple of aggregate income in market j.

We can now turn to the problem of an intermediate producer in country j. Notice that an intermediate input producer based in i selling to j will face a demand for the variety ϖ given by $q_j^I(\omega) = P_j^I \mathcal{M}_j \times \left(P_j^I\right)^{\rho-1} (p_j(\varpi))^{-\rho}$. The profits obtained by this producer when exporting in country j are thus given by equation (21) in the main text, from which the connection to the Melitz (2003) framework is evident.

B.1.2 Equilibrium with Tradable Final Goods

Consider now the case in which trade costs associated with final goods are bounded. Notice first that conditional on a demand for intermediate inputs $P_j^I \mathcal{M}_j$ in country j, the behavior of individual intermediate input producers will be identical to that in the case with nontradable final goods. There will thus again be selection into GVC participation and entry decisions will be independent market-by-market. The main complication that arises once final goods are tradable is that the demand for intermediate inputs is harder to determine because it is not only a function of aggregate income in j, but also of aggregate income in other countries where final-good exporters sell. More specifically, profits for final-good producers in (B.1) now become:

$$\pi_j^F = \left(z_j^F\right)^{\sigma-1} \left((w_j)^\gamma \left(P_j^I\right)^{1-\gamma}\right)^{-(\sigma-1)} \sum\nolimits_{k \in \mathcal{J}} \tau_{jk}^F B_k^F - w_j f_j^F,$$

where $\mathcal{J}$ denotes the set of countries in the world, as in previous sections. (Given the absence of fixed costs of exporting, final-good producers export everywhere.) Imposing free entry and noting that $B_j^F = \frac{1}{\sigma}\left(\frac{\sigma}{\sigma-1}\right)^{1-\sigma} w_j L_j P_j^{\sigma-1}$, produces a system of J equations that allows to solve for the measure of final-good producers N_j^F as a function of the vector of wages (w_j), market sizes (L_j) and parameters. Further imposing labor market clearing, allows one to solve for the vector of wages in terms of the parameters of the model. Noting that $P_j^I \mathcal{M}_j = N_j^F \times (\sigma-1)(1-\gamma) \times w_j f_j^F$, one can then compute intermediate input demand in country j. Because exported intermediate inputs get re-exported by final-good producers, this models does produce forward GVC participation in a strict sense.

The computation of this equilibrium is, however, involved and thus hard to characterize. Following Melitz (2003), it is useful to consider a world in which all J countries are symmetric and there is a unique level of final-good trade costs τ^F between country-pairs. In that case, $B_j^F = B_F$ for all $j \in J$, and it is easy to verify that intermediate input demand is given by the same expression as (20) above, although real wages are naturally higher in this variant of the model than in the one in which final goods are tradable.

B.2 Selection into Backward GVC Participation

B.2.1 Equilibrium with Tradable Final Goods

In this section, we provide the details of the extension of the Antràs et al. (2017) model to the case of tradable final goods. Suppose then that trade in final-varieties is only partially costly and involves both iceberg trade costs τ_{ij}^X as well as fixed costs f_{ij}^X of exporting. Firm behavior conditional on a sourcing strategy is largely analogous to that above. In particular, after observing the realization of its supplier-specific productivity shocks, each final-good producer will continue to choose the location of production for each input to minimize costs, which will lead to the same price index $P_i^I\left(z_i^F\right)$ for intermediate inputs as in the baseline model. The main novelty is that the firm will now produce output not only for the domestic market but also for a set of endogenously chosen foreign markets, which constitute the firm's "exporting strategy", denoted by $\mathcal{J}_i^X\left(z_i^F\right)$. We can then express the problem of determining the optimal exporting and sourcing strategies of a firm from country i with core productivity z_i^F as:

$$\begin{aligned}\pi_i^F\left(z_i^F\right) &= \left(z_i^F\right)^{\sigma-1}\left(w_i\right)^{-(\sigma-1)\gamma}\left(\kappa\sum_{k\in\mathcal{J}_i\left(z_i^F\right)}T_k\left(\tau_{ik}^I w_k\right)^{-\theta}\right)^{(\sigma-1)(1-\gamma)/\theta}\sum_{h\in\mathcal{J}_i^X\left(z_i^F\right)}\left(\tau_{ih}^X\right)^{1-\sigma}B_h\\ &\quad -w_i\sum_{k\in\mathcal{J}_i\left(z_i^F\right)}f_{ik}^M-w_i\sum_{h\in\mathcal{J}_i^X\left(z_i^F\right)}f_{ih}^X.\end{aligned}$$

Antràs et al. (2017) show that the nature of the interdependencies, as well as the theoretical results derived from them, continue to hold in this environment with active selection into both importing and exporting (see also Bernard et al., 2018). The key new feature of the above profit function is that it also exhibits increasing differences in any pair of export and import entry decisions. This has at least two implications. First, regardless of whether $(\sigma-1)(1-\gamma)\leq\theta$ or $(\sigma-1)(1-\gamma)>\theta$, any change in parameters that increases the sourcing capability of a firm – such as a reduction in any input trade cost τ_{ij}^I or f_{ij}^M, or an increase in any technology parameter T_j – will necessarily (weakly) increase the participation of the same firm in exporting. Second, restricting attention to the complements case $(\sigma-1)(1-\gamma)/\theta>1$, the model delivers a complementarity between the exporting and importing margins of firms. For instance, holding constant the vector of residual demand parameters B_i, reductions in the costs of trading final goods across countries will not only increase the participation of firms in export markets, but will also increase the number of countries from which a firm sources inputs. Furthermore, when $(\sigma-1)(1-\gamma)/\theta>1$, an increase in firm core productivity raises the firm's import *and* export participation by more than it would when one of these margins is shut down.

B.2.2 Extensions of the Antràs et al. (2017) Model

In this Appendix, we outline a series of extensions of the framework of backward GVC participation in Antràs et al. (2017).

To begin, it should be clear that it would be straightforward to follow the approach in Section 5.1.1 and recast the above framework such that the firm selecting into importing and exporting does not produce final goods, but rather intermediate inputs, which may themselves be re-exported to third countries. This would produce a framework in which a firm participates in GVCs both backwards *and* forward. It is also straightforward to reinterpret the sources of inputs in the Antràs et al. (2017) framework as regions rather than countries, so that the model can be applied to studying the formation of *domestic* production networks, as in the work of Bernard and Moxnes (2018) and Furusawa et al. (2017). As outlined in the next section, some authors have also used extensions of this framework to analyze how firms select into sourcing from particular suppliers rather than from particular locations (see Dhyne et al., 2020, for instance). Later in this survey, we will also review work – Antràs (2016) and Chor and Ma (2020), in particular – that develops incomplete-contracting extensions of the Antràs et al. (2017) framework, which permit an analysis of the extent to which backward GVC participation entails intrafirm or arm's-length intermediate input imports. Hoang (2020) has recently studied a dynamic version of the model in which the fixed costs of sourcing are sunk in nature, which leads to hysteresis in backward GVC participation, and she devises a partial identification approach to provide bounds on those sunk costs. Huang (2017) studies the implications of the model for how concentrated importing is in certain sources, and how that shapes the response of firm profitability to source-specific shocks (SARS in his empirical application), while Farrokhi (2020) applies the model to the crude oil industry to study the choice of suppliers that refineries select and how much they buy from each. In recent work, Lu (2019) and Wang (2021) have also built on the framework to study the interdependencies between the sourcing decisions of firms and the profitability of innovation and automation, respectively. Finally, Laugesen (2018) and Fan et al. (2019) both study comparative statics in the version of the model with tradable final goods, allowing the industry price index to adjust, while Fan et al. (2021) investigate the effects of input trade liberalization on the product mix of multi-product exporting firms.

B.3 Firm-to-Firm Backward GVC Participation

We next outline a model of backward GVC participation which generates firm-to-firm transactions through the selection into importing decisions of final-good producers. The model is inspired by the theoretical framework in the working paper version of Dhyne et al. (2020), which in turn extends the framework in Antràs et al. (2017).[9] The main innovation is to interpret the fixed costs of sourcing as applying at the supplier level rather than at the country (or location) level. More specifically, suppose that final-good producers can source inputs from particular suppliers in various countries only after incurring a fixed cost equal to $w_i f_{ik}^M$ units of labor, where i and k are the countries of the final-good producer and supplier respectively. Adding suppliers to the final-good firm's sourcing strategy is profitable because it lowers the price index of intermediate inputs in their cost function. Although, one could microfound via Eaton-Kortum-style assumptions why an increase in competition among suppliers reduces costs, it is simpler to just assume that the inputs produced by

[9] See Bilgin (2020) for an alternative approach extending Antràs et al. (2017) to a firm-to-firm trade setting.

different suppliers are differentiated, regardless of the country in which they are produced. If the elasticity of substitution across suppliers' inputs is constant and given by $(1+\theta)/\theta$, this produces a profit function for the final-good producer of the form:

$$\pi_i^F\left(z_i^F\right)=\left(z_i^F\right)^{\sigma-1}\left(w_i\right)^{-(\sigma-1)\gamma}\left(\kappa\sum_{k\in J}\sum_{v\in\mathcal{Z}_k}z_k^I\left(v\right)\left(\tau_{ik}^I w_k\right)^{-\theta}\right)^{(\sigma-1)(1-\gamma)/\theta}B_i-w_i\sum_{k\in J}\sum_{v\in\mathcal{Z}_k}f_{ik}^M,$$

where $z_k^I(v)$ is a parameter governing the labor productivity of supplier v in country k, $\mathcal{Z}_k$ is the set of suppliers in country k that the firm actually sources from, and where the other parameters are as defined in our rendition of the Antràs et al. (2017) framework. Given this profit function, it is straightforward to see that the bulk of the results in Antràs et al. (2017) will continue to hold here. More productive final-good producers (with higher z_i^F) will optimally invest in (weakly) larger sourcing capabilities, and if $(\sigma-1)(1-\gamma)>\theta$, they will have sourcing strategies that involve a larger set of suppliers, with their marginal supplier being less efficient than the marginal supplier of a less productive final-good producer. By the same token, more efficient suppliers will be "selected" by a larger share of final-good producers, and the marginal final-good producer will be less productive, the more productive is the supplier. These patterns very much resonate with the "negative" assortative matching patterns produced by the Bernard et al. (2018) framework and unveiled in the empirical literature, as described in Section 3.2.

B.4 Models with Stochastic Matching

Moving beyond analyses of how bilateral pairs of trade relationships are deterministically created, there is a parallel literature that has adopted tools from the network theory literature to develop stochastic models of how firm-to-firm production networks are formed. Technology and market structure are quite distinct in many of these papers, but they all share the feature that pairs of producers are formed by "chance", although the rate at which pairs form is sometimes driven by fundamental factors. An example of this type of model is the work of Eaton et al. (2018), who build on the tools from Eaton and Kortum (2002) to develop a model in which final-good producers get randomly matched with heterogeneous suppliers. Final-good producers have full bargaining power, so each input (or task) is bought at its unit cost, and only from the least-cost supplier of each input. When a final-good producer can produce an input (or perform a task) more cheaply than any other supplier, that task is not outsourced and is instead part of the firm's value added (value added and inputs are perfect substitutes in their setting, unlike all models we have reviewed so far). Eaton et al. (2018) ingeniously choose functional forms and productivity distributions to obtain a neat characterization of the general equilibrium of the model, which allows them to shed light on features of the labor share in French manufacturing, and how it is shaped by trade integration.

Another related work is Oberfield (2018), who also provides a theory of the formation of firm-to-firm links in which random matching plays a key role. Oberfield (2018) consider a setting in which firms produce output combining labor with an input provided by another firm, according to a Cobb-Douglas production function. The productivity with which labor and the input are combined is buyer-seller specific (or *match*-specific) and characterized by a Pareto distribution with shape parameter θ. Furthermore, each final-good producer (or buyer) chooses the best match among a pool of potential suppliers, with the number of available potential suppliers characterized by a Poisson distribution. For the case of a closed economy in which all producers' output can, in principle, be used as an input by any other firm, Oberfield (2018) shows that this formulation delivers a Fréchet distribution labor productivity, just as in Eaton and Kortum (2002). A key feature of Oberfield's framework is that particularly productive suppliers are likely to be employed by many firms, who in turn become more productive themselves by employing these highly productive suppliers. This feedback loop very much resonates with the mechanics of the Bernard et al. (2018) model described above. As Oberfield (2018) shows, an implication of these complementarities is that his model generates large differences in productivity and size across firms, and particularly so when the elasticity of output with respect to intermediate inputs is high.

Both the Eaton et al. (2018) and Oberfield (2018) frameworks are static in nature, but a growing number of papers have considered dynamic environments in which firm-to-firm links are shaped by randomness, but in which the stock of those links evolves over time. A pioneering study in a trade context is the work of Chaney (2014), who considers a model in which producers accumulate a set of customers or buyers over time. This process of link formation takes two forms. First, a firm meets new partners at random but in a way that is biased toward the location of the firm, with local matches more frequent than distant ones. Second, once a firm has acquired a network of distant contacts, it also acquires new customers as if it was producing from those locations. Chaney (2014) describes the dynamic evolution of firm-to-firm links, and shows that it is in line with several features of granular French firm-level export data. For instance, his framework predicts and the evidence confirms that the average squared distance of exports is a power function of firm size, and that the dynamic process of match formation generates path-dependence in a firm's export growth, along the lines of the empirical findings of Morales et al. (2019). In a follow-up paper, Chaney (2018) shows that a similar process of network formation can explain why trade flows tend to decline with distance with close to a unit elasticity.

Lim (2018) proposes an alternative framework for the dynamics of network formation. He first outlines a framework that is analogous to the model of exporting (or forward GVC participation) in Bernard et al. (2018) with two exceptions. First, he considers production technologies that feature the same degree of substitution between labor and inputs as across inputs, and second, as in Oberfield (2018), he assumes that firms' output can be indistinguishably sold to consumers or to other firms as inputs (so firms are neither exclusive final-good producers nor exclusive input producers). In order to be able to sell to other firms, firms need to incur fixed costs, and as in the frameworks above, larger and more productive firms will have more firm-to-firm links, both because they can better amortize the fixed costs of generating links, but also because other firms will find it profitable to pay the cost to set up links with them. Despite the complex nature of the model, Lim (2018) provides a neat characterization of its equilibrium in a closed economy. He then introduces dynamics of link formation by assuming that both firms' fundamentals (demand shifters and core productivity) as well as the costs of maintaining relationships follow a first-order Markov process. These features allow Lim (2018) to study the effects of business cycles on productivity, and the contribution of the entry and exit of firm-to-firm links for economic fluctuations. In more recent work, Huneeus (2018) presents an open-economy extension of the model in Lim (2018), which permits a study of the rich implications of international trade shocks – which are salient in his Chilean application – and how these shocks percolate along domestic production networks.

B.5 Snakes and Scale Economies

In this Appendix, we describe the challenges that one encounters when incorporating increasing returns to scale and trade costs in models of sequential GVCs.

To build intuition, let us first consider a case with no trade costs and no TFP differences across countries. To model increasing returns to scale in the simplest possible manner, suppose that marginal costs continue to be independent of scale and are given by the Cobb-Douglas technology in (24), but now assume that in order to activate country $j \in \mathcal{J}$ as a candidate location to produce stage n, the lead firm needs to incur a fixed cost equal to f_{ij} in terms of labor in the home country i of the lead firm. It should be clear that conditional on a subset of activated countries $\mathcal{J}_i \subseteq \mathcal{J}$, what one might call the lead firm's *GVC strategy*, the problem is analogous to that outlined in equation (25) except that the lead firm considers a smaller set of candidate location. Conditional on the profits obtained under alternative GVC strategies, the firm will then choose the strategy that delivers it the highest profit flow. In deciding whether to add a location, the firm will trade off the achieved marginal cost savings (and associated higher operating profits) with the upfront fixed cost. This tradeoff is quite similar to the one studied by Antràs et al. (2017) and overviewed in Section 5.1.2 above. In fact, if one assumes that the firm faces an isoleastic demand function, and the productivity terms $1/a^n_{\ell(n)}$ are drawn from a Fréchet distribution (independently across locations and inputs), $F_i(z) = \exp\{-T_i z^{-\theta}\}$, the resulting profit function for a given GVC strategy is given by:

$$\pi_i^F\left(z_i^F\right) = \left(\kappa \sum_{k \in \mathcal{J}_i} T_k \left(c_k\right)^{-\theta}\right)^{(\sigma-1)/\theta} B_i - w_i \sum_{k \in \mathcal{J}_i} f_{ik},$$

where B_i is a residual demand term. It should be clear that this profit function is identical to that in equation (23) when $z_i^F = 1$, $\tau_{ij}^I = 1$ for all i, j, and $\gamma = 0$. The choice of the set of locations the lead firm activates can thus be studied using the exact same tools as developed in Antràs et al. (2017) (assuming, of course, that the set of activated countries is decided prior to the start of production).

The case with trade costs is, however, much harder to study. Intuitively in such a case, the *lead firm* problem cannot be solved independently for each destination market j, because whether a location ℓ constitutes a cost-minimizing location for stage n in a particular chain ending in j will be a function of the scale of this production node, and the latter is shaped by the overall level of production flowing through this node (potentially involving chains ending in destination markets other than j). As a result, dynamic programming ceases to be a powerful tool to simplify the problem (see de Gortari, 2020, for more details, and for an attempt to circumvent these complications).

Another approach to illustrate the complications that arise from the interaction of multi-stage production, trade costs and scale economies is to study a stylized general equilibrium model in which all firms produce a homogeneous good that requires N stages that can be produced in any of $J = N$ countries. Furthermore, assume the same sequential cost function as in (24), but now assume $z_{\ell(n)} = 1$ and $a^n_{\ell(n)} = (L^n_i)^{-\phi}$, where ϕ captures the role of external economies. Antràs and de Gortari (2016) study this environment and assume that ϕ is large enough to ensure a complete specialization equilibrium in which each stage is produced in exactly one country. Assuming logarithmic preferences and solving for the assignment of stages to countries that maximizes utilitarian world welfare, Antràs and de Gortari (2016) show that this problem solves:

$$\boldsymbol{\ell} = \{\ell(1), \ell(2), ..., \ell(N)\} = \arg\min \sum_{i=1}^{N} \ln \tau_{\ell(N)i} + \sum_{n=1}^{N-1} \beta_n \ln \tau_{\ell(n)\ell(n+1)}, \tag{B.2}$$

where β_n is defined in (26). Intuitively, the optimal sequencing of production will simply seek to minimize the trade costs associated with the production process traveling through each of the J countries, "visiting" each country exactly one time, and then returning to all countries in the form of a finished product. Antràs and de Gortari (2016) draw a connection between the optimization problem in (B.2) and the minimal distance Hamiltonian path problem in graph theory, or the associated travelling salesman problem (TSP) in combinatorial optimization. It is well known that both of these problems are NP-hard as they entail picking an optimal sequencing out of the $N!$ possible permutations of countries in the value chain, and dynamic programming techniques are ineffective in reducing the dimensionality of those problems.[10]

B.6 Horizontal and Export-Platform FDI

Although models combining global production strategies, increasing returns to scale, and trade costs are hard to work with, there is a specific version of those models which has been extensively studied in the literature. This corresponds to a variant of the models studied above in which $N = 1$, so only final goods are produced, and this is done with local factors of production. Unlike in models of exporting, however, lead firms are not constrained from producing only in the origin country (e.g., the country where they paid the fixed cost of entry). They can instead set up foreign assembly plants to service foreign consumers at a lower marginal cost. These strategies clearly connect with the voluminous literature on horizontal FDI and export-platform FDI, which was overviewed in Chapter 2 of the 4th volume of this *Handbook* (see Antràs and Yeaple, 2014, in particular, Section 6.1). Because some of the papers in this literature neatly connect with many firm-level models of GVCs reviewed above, it is however worth briefly reviewing some of their key contributions and insights.

Following the lead of Tintelnot (2017), we envision a two-stage problem in which a lead firm

[10] There is however a key difference between the problem in (B.2) and the TSP: due to the compounding effect of trade costs, the optimal assignment will put a larger weight on reducing trade costs at relatively downstream stages than at stages further upstream, a result reminiscent to the one in Antràs and de Gortari (2020).

based in country i first activates a set of locations $\mathcal{J}_i \subseteq \mathcal{J}$ after incurring a fixed cost equal to $w_i f_{ik}$ when activating country k, and then decides from which assembly plant in $\mathcal{J}_i$ to sell to consumers in all potential destinations j. The second stage is well captured by the more general problem in equation (28) when setting $N = 1$, which reduces to:

$$\ell^j = \arg \min_{\ell^j(N) \in \mathcal{J}_i} p_j^F\left(\ell^j\right) = \arg \min_{\ell \in \mathcal{J}_i} \{\tau_{\ell j} a_\ell c_\ell\}. \tag{B.3}$$

when $N = 1$ (where we have dropped n subscripts for simplicity). In words, consumers from j will be serviced from a plant located in the country $\ell^j(N) \in \mathcal{J}_i$ that minimizes the delivery cost of the good $\tau_{\ell j} a_\ell c_\ell$. In order to discern how many assembly plants the firm should set up and where they will be located, one needs a structure to transition from the problem to a profit function. As in many of the papers reviewed above, Tintelnot (2017) assumes that the firm faces an isoelastic demand function, and the productivities $1/a_\ell$ are drawn from a Fréchet distribution (that is independent across locations). The main new trick that Tintelnot (2017) develops is to assume that firms produce a continuum of consumer goods, which together with the Fréchet assumption, delivers gravity-style equations representing the bilateral sales of all the firm's plants. More specifically, the share of the firm's sales in market j originating from assembly plants in country k is given by:

$$\mu_{ikj} = \frac{T_k(\tau_{kj}c_k)^{-\theta}}{\sum_{k' \in \mathcal{K}_i} T_{k'}(\tau_{k'j}c_{k'})^{-\theta}}, \tag{B.4}$$

where $\mathcal{K}_i$ is the set of countries or locations where the firm has assembly plants, and where the other parameters are as defined in previous models. Furthermore, one can express the firm's profits conditional on an assembly strategy $\mathcal{K}_i$ as:

$$\pi_i(\mathcal{K}_i) = \kappa \sum_{j \in J} B_j \left(\sum_{k \in \mathcal{K}_i} T_k (\tau_{kj} c_k)^{-\theta} \right)^{(\sigma-1)/\theta} - w_i \sum_{k \in \mathcal{K}_i} f_{ik}, \tag{B.5}$$

where κ is a constant, and B_i is a residual demand term. For the price index associated with the bundle of varieties produced by the firm to be bounded, Tintelnot (2017) shows that one needs to impose $\sigma - 1 < \theta$. This parametric restriction implies that the model features "market cannibalization" effects: a firm may find it optimal to set up a plant in country k to reduce the costs of selling goods to consumers in country k and nearby countries, but such a decision necessarily reduces the marginal benefit of setting up plants in other countries $k' \neq k$. Using the terminology in Antràs et al. (2017), the firm's assembly strategy features substitutability (or decreasing differences) in the entry decisions in alternative markets. Thus, although choosing an assembly strategy amounts to choosing a set among 2^J possible sets, the problem can in principle be solved using the algorithm suggested in Arkolakis and Eckert (2017). In his empirical application, which focused on the horizontal and export-platform strategies of German multinationals, Tintelnot (2017) instead restricted the analysis to a case in which $J = 12$, so he could solve the computational problem by brute force.

In recent work, Antràs et al. (2020) develop a multi-country model in which firms choose not only the locations of their various assembly plants, as in the horizontal FDI and export-platform literature, but also the countries from which all those plants import inputs, as in the global sourcing literature. The model in Antràs et al. (2020) constitutes a marriage of the Tintelnot (2017) model of export-platform FDI and the global sourcing framework in Antràs et al. (2017). Their framework delivers simple gravity-style formulas for both firm-level bilateral shipments of consumer goods from any country where a firm assembles finished goods to all other countries in the world, as well as firm-level bilateral purchases of intermediate inputs from countries in a firm's sourcing strategy to each country in which that same firm assembles final goods. Crucially, their framework identifies a natural complementarity between these two decisions – as hinted in prior work by Yeaple (2003) and Grossman et al. (2006) – and thus delivers novel implications for the role of geography in shaping the global production strategies of firms. Intuitively, a richer sourcing strategy reduces marginal costs, increases optimal firm scale, and thus makes a richer assembly strategy more appealing (or its associated fixed costs easier to amortize). Similarly, a richer assembly strategy increases overall firm sales and thus makes a more expansive sourcing strategy more appealing (or its associated fixed costs easier to amortize). Empirically, Antràs et al. (2020) merge US Census domestic and trade data with the US Bureau of Economic Analysis (BEA) comprehensive surveys on multinational activity to document a series of novel facts regarding the global assembly and global sourcing strategies of US-based firms, and they develop new tools to estimate their model structurally and to perform counterfactual exercises that illustrate the rich implications of changes in trade costs on global production patterns. More specifically, due to the coexistence of sources of substitutability (market cannibalization) and complementarity in the model, the problem of determining a firm's extensive margin decisions does not feature the type of "single-crossing" properties that typically rationalize the use of iterative algorithms to reduce the dimensionality of the problem, as in Jia (2008), Antràs et al. (2017) or Arkolakis and Eckert (2017). To make progress on this issue and render feasible a structural estimation of the model, Antràs et al. (2020) develop a probabilistic approach to solve the firm's extensive margins of global sourcing and global assembly, which smooths out the firm's problem and allows them to characterize its solution by studying and computationally approximating the first-order conditions of this problem via Monte Carlo integration.

We have thus far described recent contributions that tightly connect with other theoretical work described in this Chapter, but it is worth closing this section with a brief description of other recent work on the horizontal or export-platform FDI dimensions of the GVC strategies of lead firms.

First, and as already described in Antràs and Yeaple (2014), Arkolakis et al. (2018) develop a multi-country model in which lead firms decide which country i to enter in, and from which country k to service consumers in each country j. As in the work of Tintelnot (2017), this appears to be a complex combinatorial problem. Arkolakis et al. (2018) achieve tractability by abstracting away from fixed costs of setting up assembly plants, and only modeling fixed costs of marketing goods in country j regardless of the origin of production k. This basically turns the problem of figuring out the source of goods k as one that minimizes marginal costs, as in the work of Eaton and Kortum

(2002). Yet the presence of marketing costs implies that individual firms may only produce in and sell to a subset of countries. By making suitable assumptions about the distribution of productivity across goods and countries, Arkolakis et al. (2018) further show that their framework delivers simple expressions for bilateral trade flows across countries, some of which reflect standard exporting, while the rest reflect export-platform sales.

Arkolakis et al. (2018)'s framework also incorporates iceberg-style costs associated with firms assembling goods in countries other than their country of incorporation. This added cost can be interpreted as a reduced-form way to capture the costs of importing inputs (Ramondo and Rodríguez-Clare, 2013) or knowledge (Keller and Yeaple, 2013) from the headquarters, or perhaps the costs of adapting production to a foreign and unfamiliar environment. An alternative cost of multinational activity features prominently in the recent work of Head and Mayer (2019), who argue that firms also incur adaptation costs when marketing goods in countries distinct from their origin country, regardless of where those goods are produced. They argue that this is an especially important feature of the car industry, and they estimate an industry equilibrium model in which car makers decide on the optimal sourcing of their car models taking into account where their headquarters are located, where they have assembly plants (which are fixed in their model), and where consumers are. Another novel feature of their framework is the inclusion of external economies of scale, which they argue are also a key feature of the industry under study.

B.7 Contractual Frictions and Firm Boundaries in Spiders

Let us return to the model of backward GVC participation developed in Section 5.1.2. Remember that the framework features a final-good sector with CES preferences over differentiated varieties and an intermediate-input sector that provides differentiated input varieties to the final-good sector, which combines them with labor in production according to equation (17). The bundle of intermediate inputs is also characterized by a CES aggregator, as in equation (18). The final good-sector features increasing returns to scale technologies and is monopolistically competitive, while the upstream sector produces under constant returns to scale with productivity levels drawn from a Fréchet distribution. Final-good varieties are nontradable, but intermediate inputs can be traded across borders with associated iceberg trade costs τ_{ij}^{I}.

Chor and Ma (2020) embeds a property-rights model of firm boundaries à la Antràs (2003) and Antràs and Helpman (2004) into this framework.[11] More specifically, the following new assumptions are made. First, each input variety ϖ is produced combining headquarter services and a manufacturing input provided by the supplier according to a Cobb-Douglas technology:

$$y_{ij}^{s}\left(\omega,\varpi\right)=z_{ij}^{I}\left(\omega,\varpi\right)\left(h_{ij}\left(\omega,\varpi\right)\right)^{\eta}\left(m_{ij}\left(\omega,\varpi\right)\right)^{1-\eta}, \tag{B.6}$$

where η reflects the headquarter-intensity of input production. Second, both headquarter services and the supplier input are relationship-specific in the sense that they are each customized as inputs

[11] To be precise, Chor and Ma (2020)'s framework incorporates multiple upstream sectors, but we only model one here for simplicity.

for the final-good producers' consumption variety. Third, certain aspects of the production of both headquarter services and of input manufacturing cannot be specified in a fully enforceable manner in an initial contract between the final-good producer and the supplier. A simple way to model this, following Acemoglu et al. (2007) and Antràs and Helpman (2008), is to assume that only a fraction μ_{ij}^{h} of the tasks that go into producing headquarter services and a fraction μ_{ij}^{m} of the tasks that go into producing manufacturing inputs are contractible. With a symmetric Cobb-Douglas technology across tasks, this amounts to rewriting technology in (B.6) as:

$$y_i^s(\varpi) = z_{ij}^I(\omega,\varpi)\left(\left(h_{ij}^c(\omega,\varpi)\right)^{\mu_{ij}^h}\left(h_{ij}^n(\omega,\varpi)\right)^{1-\mu_{ij}^h}\right)^{\eta}\left(\left(m_{ij}^c(\omega,\varpi)\right)^{\mu_{ij}^m}\left(m_{ij}^n(\omega,\varpi)\right)^{1-\mu_{ij}^m}\right)^{1-\eta},$$

where $h_{ij}^c(\omega,\varpi)$ and $m_{ij}^c(\omega,\varpi)$ are the symmetric investments in contractible tasks, and $h_{ij}^n(\omega,\varpi)$ and $m_{ij}^n(\omega,\varpi)$ are the analogous investments in non-contractible tasks. Finally, because some investments are not contractible ex-ante, one needs to specify how the terms of exchange will be determined ex-post, once all investments have been incurred.[12] As is standard in the literature, Chor and Ma (2020) characterize this ex-post bargaining using the Nash Bargaining solution and assume symmetric information between headquarters and the various suppliers. In that bargaining, the final-good producer walks away with a share β_{ij} of the surplus from the relationship, with this surplus in turn related to the contribution of all the other suppliers into production. The share β_{ij} may be shaped by primitive bargaining power or relationship-specificity asymmetries (see Antràs, 2016; Eppinger and Kukharskyy, 2020), but crucially and following the property-rights approach, it is also shaped by firm boundary decisions. When the supplier is integrated, the final-good producer obtains a share β_{ij}^V of surplus that is higher than the share β_{ij}^O it obtains when the supplier is a stand-alone firm.

The Chor and Ma (2020) model is much richer than the underlying Antràs et al. (2017) framework, but it is simpler in an important sense: Chor and Ma (2020) abstract from fixed costs of importing, and thus firms source inputs from all countries in the world. Nevertheless, firms' sourcing strategies are richer in the sense that the firm has $2J$ potential sources for each input, corresponding to the J countries and two organizational forms (vertical integration versus outsourcing). To capture the intuitive notion that the productivity of integrated and independent suppliers in a given country i should be correlated, Chor and Ma (2020) assume that the productivity term $z_{ij}^I(\omega,\varpi)$ in (B.6) is drawn independently for each ω and ϖ from a "nested-Fréchet" distribution with cumulative distribution function (cdf):

$$\Pr\left(z_{1j}^V(\omega,\varpi)\leq z_{1j}^V, z_{1j}^O(\omega,\varpi)\leq z_{1j}^O,\ldots,Z_{Jj}^O\leq z_{Jj}^O\right) = \exp\left\{-\sum_{i=1}^{J}T_i\left(\left(z_{ij}^V\right)^{-\frac{\theta}{1-\lambda_i}}+\left(z_{ij}^O\right)^{-\frac{\theta}{1-\lambda_i}}\right)^{1-\lambda_i}\right\},$$

[12]The initial contract specifies binding investment levels for all contractible tasks, as well as a lump-sum transfer between the agents.

where $T_i^k > 0$, $\theta^k > 1$ and $0 < \lambda_i < 1$ for each source country i. The parameters λ_i govern the correlation in the productivity draws obtained by stand-alone and integrated suppliers, with $\lambda_i = 1$ implying an identical productivity, and $\lambda_i = 0$ for all countries i corresponding to the special case where the $2J$ draws are each from independent Fréchet distributions with cdf: $\exp\left\{-T_i(z_{ij})^{-\theta}\right\}$. This specification delivers a closed-form expression for sourcing shares that has an intuitive nested logit form: The share of inputs obtained from country i under (say) integration is equal to the share sourced from country i, multiplied by the share sourced under integration conditional on having chosen country i. Furthermore, these shares are not only shaped by standard parameters, such as levels of technology, trade costs and wages, but also by institutional or contractual parameters, such as the degrees of contractibility μ_{ij}^h and μ_{ij}^m, and the bargaining parameters β_{ij}^V and β_{ij}^O.

The fact that Chor and Ma (2020) ignore the extensive margin of which source countries and organizations to activate allows them to neatly characterize the general equilibrium of the model, and compare it to recent quantitative models in the field. For instance, the framework delivers an expression for the welfare gains from trade that is akin (in the limit case where all inputs are fully contractible) to that in Arkolakis et al. (2012). They also show that their framework is amenable to the use of the hat-algebra approach to counterfactuals in Dekle et al. (2008) and Caliendo and Parro (2015), which they use to evaluate the welfare consequences of improving the contractual environment, as well as to study the way in which the magnitude of the gains from trade interacts with the level of contracting institutions.

B.8 Contractual Frictions and Firm Boundaries in Snakes

We next turn to a parallel set of studies of how contractual frictions shape the location and organization of GVCs, but this time we focus on purely sequential production process. We begin overviewing the work of Antràs and Chor (2013) and Alfaro et al. (2019) who develop and test the implications of a property-rights model of sequential production.

The setting is similar to the models described in Sections 4.2 and 5.2.1, except that production stages are characterized as a continuum. More specifically, Antràs and Chor (2013) focus on the problem of a final-good producer facing an isoelastic demand for its product, that is seeking to optimally organize a sequential manufacturing process that requires the completion of a unit measure of production stages. These stages are indexed by $\varpi \in [0, 1]$, with a larger ϖ corresponding to stages further downstream and thus closer to the finished product. Denote by $y^s(\omega, \varpi)$ the value of the services of intermediate inputs that the supplier of stage ϖ delivers to the firm. Production of final-good variety ω is then given by:

$$y^F(\omega) = z^F(\omega)\left(\int_0^1 y^s(\omega, \varpi)^\rho \mathcal{I}(\varpi)\, d\varpi\right)^{1/\rho}, \tag{B.7}$$

where $z^F(\omega)$ is a productivity parameter, $\rho \in (0, 1)$ is a parameter that captures the (symmetric) degree of substitutability among the stage inputs (as in equation (17)), and $I(\varpi)$ is an indicator function that takes a value of 1 if input ϖ is produced after all inputs $\varpi' < \varpi$ have been produced, and a value of 0 otherwise. It is this last indicator function $\mathcal{I}(\varpi)$ that makes the production technology inherently sequential.

The contractual aspects of the model are in many ways analogous to those discussed above in the Chor and Ma (2020) framework. The different stage inputs are provided by suppliers, who each undertake relationship-specific investments to make their components compatible with those of other suppliers along the value chain. The setting is one of incomplete contracting, in the sense that contracts contingent on whether components are compatible or not cannot be enforced by third parties. As a result, the division of surplus between the firm and each supplier is governed by bargaining, after a stage has been completed and the firm has had a chance to inspect the input. At that point, the firm and the supplier negotiate over the division of the incremental contribution to total revenue generated by supplier ϖ, independently from the bilateral negotiations that take place at other stages (see Antràs and Chor, 2013, for alternative formulations of the bargaining protocol). In the initial stage of the model, the firm must decide which input suppliers (if any) to own along the value chain. As in the property-rights theory, the integration of suppliers does not change the space of contracts available to the firm and its suppliers, but it affects the relative ex-post bargaining power of these agents. Vertical integration confers the final-good producer higher bargaining power than outsourcing.

In order to solve for the subgame perfect equilibrium of the above game, Antràs and Chor (2013) note that the quasi-rents over which the firm and the supplier at position ϖ in the value chain negotiate are given by the incremental contribution to total revenue generated by supplier ϖ at that stage, which in turn are given by:

$$r'(\omega,\varpi) = \kappa\left(z^F(\omega)\right)^{\rho}(r(\omega,\varpi))^{1-\frac{\sigma-1}{\sigma\rho}}(y^s(\omega,\varpi))^{\rho}, \tag{B.8}$$

where $r(\omega,\varpi)$ is the revenue *secured* by the final-good producer up to stage ϖ. As highlighted by Antràs and Chor (2013), whenever $\sigma > 1/(1-\rho)$, the investment choices of suppliers are *sequential complements* in the sense that higher investment levels by prior suppliers increase the marginal return of supplier ϖ's own investment $y^s(\omega,\varpi)$. Conversely, if $\sigma < 1/(1-\rho)$, investment choices are *sequential substitutes* because high values of upstream investments reduce the marginal return to investing in $y^s(\omega,\varpi)$. Because the supplier at position ϖ chooses $y^s(\omega,\varpi)$ to maximize $(1-\beta(\omega,\varpi)))\,r'(\omega,\varpi)-c(\omega,\varpi)y^s(\omega,\varpi)$, where $c(\omega,\varpi)$ is the marginal cost of investment, equation (B.8) illustrates the trickle-down effect that upstream investment inefficiencies can have on downstream stages.

Exploiting the recursive structure of the model, Antràs and Chor (2013) characterize the optimal division of surplus along the chain. The key result in their paper is that the relative size of the input and final-good elasticities of substitution, respectively $\sigma_\rho = 1/(1-\rho)$ and σ, governs whether the incentive for the final-good producer to retain a larger surplus share increases or decreases along the value chain. Intuitively, when σ is high relative to σ_ρ, investments are sequential complements, and high upstream values of $\beta(\omega,\varpi)$ are particularly costly since they reduce the incentives to invest not only of these early suppliers but also of all suppliers downstream. Conversely, when σ is small relative to σ_ρ, investments are sequential substitutes, and low values of $\beta(\omega, \varpi)$ in upstream stages are now relatively detrimental, since they reduce the incentives to invest for downstream suppliers, who are already underinvesting to begin with.

Alfaro et al. (2019) develop several extensions of the Antràs and Chor (2013) model that are relevant for their firm-level empirical analysis. First, they introduce asymmetries across inputs and map them to variation across inputs in the degree of contractibility. Second, they incorporate heterogeneity across final-good producers in their core productivity, while introducing fixed costs of integrating suppliers, as in Antràs and Helpman (2004). They then show how such productivity differences influence the number of stages that are integrated, and hence the propensity of the firm to integrate upstream relative to downstream stages. Finally, they consider a scenario in which integration is infeasible for certain segments of the value chain, for example, due to exogenous technological or regulatory factors, and demonstrate that the model's predictions continue to describe firm boundary choices for those inputs over which integration is feasible.

Although Antràs and Chor (2013) and Alfaro et al. (2019) abstract from the study of location choices, their results have potentially interesting implications for the choice between domestic and foreign sourcing whenever these sourcing strategies are associated with different levels of contract enforcement. To see this, consider the case in which contracting in domestic transactions is complete, while foreign sourcing is associated with incomplete contracting (as in Antràs, 2005). The results in Antràs and Chor (2013) then suggest that, in the sequential complements case ($\sigma > \sigma_\rho$), foreign sourcing is particularly unappealing in upstream stages. Thus, if domestic and foreign sourcing coexist along the value chain, then only relatively downstream inputs will be offshored. Conversely, in the sequential substitutes case, ($\sigma < \sigma_\rho$) one would expect relatively upstream stages to be offshored. In sum, the model predicts that the "upstreamness" of an input should be a relevant determinant of the extent to which it is procured from foreign suppliers, with the sign of that dependence being crucially shaped by the relative size of σ and σ_ρ.

In largely contemporaneous work, Fally and Hillberry (2018) developed an alternative framework illustrating the consequences of contractual frictions for the location and organization of GVCs. Their framework in turn builds on the insightful transaction-cost model in Kikuchi et al. (2018). In that framework, production of a final good requires (again) that a continuum of stages or tasks be executed in a pre-determined order. A set of identical firms can produce any set of tasks with decreasing returns with respect to the measure of tasks produced, which fosters specialization across firms. To put a check on specialization and generate firms that produce a measurable set of tasks, Kikuchi et al. (2018) assume that firm-to-firm transactions involve a cost that is proportional to the value and price of the good at the time of delivery. Kikuchi et al. (2018) provide a sharp characterization of this problem, in part using recursive methods. For reasons analogous to those in Costinot et al. (2013) and Antràs and de Gortari (2020), the resulting allocation has relatively small firms in the upstream stages of production, with firm size growing monotonically as one moves to more and more downstream stages. The authors claim that the model can match the size distribution of firms and they further provide a set of comparative statics with respect to transaction costs, and parameters of the cost function. Fally and Hillberry (2018) extend this setup to an international setting with costly trade, and develop implications for within-chain comparative advantage. Fally and Hillberry (2018) demonstrate that their framework delivers a positive relationship between a country-industry pair's upstreamness measure and its gross-output-to-value-added ratio, and they provide empirical evidence consistent with it.

B.9 Search Frictions and Relational Contracting

B.9.1 Search Frictions

The standard way to model these frictions is by assuming that the type of fixed-cost investments firms incur to match with GVC partners, as modelled in Sections 5.1.1, 5.1.2 and 5.1.3, only deliver matches with a probability governed by the relative mass of firms searching for matches in both sides of the market. The work of Grossman and Helpman (2005) constitute an early contribution to this literature in a simple two-country general equilibrium model, while in more recent work, Eaton et al. (2014), Allen (2014), Krolikowski and McCallum (2018) and Lenoir et al. (2019) adopt a similar approach in more complex, multi-country quantifiable models.[13]

The introduction of search frictions enriches the set of predictions emanating from models of firm-level GVC participation. Without delving into the technical details of these models, we would highlight four main new sets of insights. First, other things equal, it is clear that search frictions reduce the attractiveness of engaging in GVC activity, and might lead some firms to opt out of it when they would have found it profitable to participate in the absence of these frictions. This in turn carries consequences for the welfare responses to trade shocks and for the trade elasticity, relative to models without search frictions (see Krolikowski and McCallum, 2018). Second, in the presence of increasing returns in the matching function, this line of models can generate multiple equilibria and *waves* of GVC participation, as the entry of some firms may generate positive spillovers on the entry of other firms (see McLaren, 2000; Grossman and Helpman, 2002). Third, because the fixed costs associated with matching with other producers are sunk in nature, this line of models also tends to feature hysteresis in the margins of trade (see Eaton et al., 2014), which in turn has implications for how the geography of GVCs responds to shocks, such as the current COVID-19 pandemic (see Antràs, 2020). Fourth, this hysteresis can also be interpreted as a form of lock-in effect, which binds buyer-seller pairs together, and thus aggravates the type of contractual frictions outlined in Sections 5.3.1 and 5.3.2.

A natural way to reduce search frictions in finding suitable GVC partners is to rely on specialized intermediaries. It is thus not surprising that recent work on intermediation in international trade has also developed frameworks in which search frictions are prominent, as in the work of Antràs and Costinot (2011), Dasgupta and Mondria (2018), or Startz (2016).

[13]See also McLaren (2000) and Grossman and Helpman (2002) for even earlier contributions with search frictions. Other authors refer to the costs of matching as search costs – see Monarch (2020) or Antràs et al. (2020)– but in this section we focus attention on settings in which the probability of a match is a function of the sets of agents searching.

B.9.2 Relational Contracting

As we have argued in Sections 5.3.1 and 5.3.2, the relational nature of GVCs highlights the role of institutional quality as a significant determinant of GVC participation. Nevertheless, the same forces that make relational GVCs rely intensively on institutional quality, such as the lock-in effects created by relationship-specific investments and by search frictions, also make GVC links particularly "sticky", which fosters the emergence of reputational mechanisms of cooperation which might partly substitute for the absence of formal contracting.

An extreme version of this type of relational contracting arises when parties involved in a GVC altogether bypass the market mechanism and decide to transact within firm boundaries, as in the work outlined in Sections 5.3.1 and 5.3.2. Nevertheless, the internalization of transactions in a GVC is just one of the many organizational responses to the contractual vagaries associated with cross-border transactions. In an influential study in the management literature, Gereffi et al. (2005) elaborate on a much more extensive taxonomy of potential governance forms within GVCs, and various researchers have built on their work to shed light on the relative prevalence of these governance forms through a number of interesting case studies (see Van Biesebroeck and Schmitt, 2020, for a recent example in the economics literature).

Because trade economists typically favor modes of governance that can be identified in the data across various industries, the literature in international trade has largely focus on exploring the emergence and consequences of relational contracting. This is perceived as an intermediate option between vertically integrated GVC links and spot market transactions with suppliers. We reviewed the burgeoning empirical trade literature on relational contracting in Section 3.3. Here, we simply outline some of the theoretical insights from that literature.

It is useful to begin by identify two broad approaches to modeling how relational contracting shapes GVC participation and trade flows. The first approach, which one might call the "adverse selection" approach, considers environments in which certain GVC participants – say buyers – come in two fixed types: honest and dishonest. Honest buyers always honor contracts (say paying for the delivered goods), even when the contractual environment is weak and cannot always impose penalties on misbehavior. On the other hand, dishonest agents misbehave when given a chance, which in these models occurs with certain probability. In this environment, repeated contracting allows sellers to better learn and identify whether buyers are honest or dishonest. More precisely, starting from a prior, sellers update their belief of the buyer being honest as long as no misbehavior is observed in equilibrium. Yet, when misbehavior is observed, sellers immediate infer they are dealing with a dishonest buyer, and optimally discontinue the relationship. This line of models is developed in Antràs and Foley (2015) and Araujo et al. (2016), and it has been further developed and taken to the data by Monarch and Schmidt-Eisenlohr (2017), a paper we discussed in some detail in Section 3.3. A distinguishing feature of these line of models are that they naturally generate an increasing volume of trade as relationship age increases, with the rate of growth in firm-to-firm trade being larger, the weaker the contractual environment.

A second line of models, which we can refer to as "moral hazard" approaches are more in line with the models of contractual frictions reviewed in sections 5.3.1 and 5.3.2. These frameworks build on the relational contracting literature (see MacLeod and Malcomson, 1989; Levin, 2003; Board, 2011), in which agents undertake noncontractible investments, and in which repeated interactions may allow them to sustain cooperation under the threat of reversion to a non-cooperative equilibrium. This literature is largely concerned with characterizing the range of parameter values for which cooperation can be sustained. A particularly noteworthy contribution is the work of Defever et al. (2016) who study a model of global sourcing (or backward GVC participation) very much in the spirit of the double-sided holdup problem in Antràs (2003), Antràs and Helpman (2004) and Chor and Ma (2020) (see Section 5.3.1). An intuitive insight from these models is that relational contracting is more likely to be used whenever agents are relatively patient, in which case the costs of reverting to a non-cooperative equilibrium are higher. Less trivially, these frameworks also illustrate how weak contracting, by depressing the payoffs under non-cooperation, renders relational cooperation more beneficial. In this sense, formal and informal contracting appear to be substitutes. An unappealing (or counterfactual) implication of these line of frameworks – at least in their most stripped-down form – is that they tend to general first-best investment levels and trade volumes from the onset of a relationship. To remedy this, some authors such as Macchiavello and Morjaria (2015), have considered environments that blend the adverse selection and moral hazard approaches.[14]

In closing, it is also worth mentioning some theoretical work, building on Baker et al. (2002), that has developed frameworks in which firms not only choose between engaging in spot versus relational contracting, but also consider the possibility of internalizing transactions, as in the work reviewed in Sections 5.3.1 and 5.3.2. Notable contributions to this literature include the work of Kukharskyy (2016) and Kamal and Tang (2014).

C Trade Policy in the Age of GVCs

C.1 Effective Rate of Protection and Tariff Escalation

Corden (1966)'s definition of the effective rate of protection is "*the percentage increase in value added per unit in an economic activity which is made possible by the tariff structure relative to the situation in the absence of tariffs*" (p. 222). To formally study this concept, consider a simple partial-equilibrium environment in which final output in a given industry is produced with local value added and with a bundle of intermediate inputs, as in many of the models studied in previous sections. It is assumed that local value added subsumes any usage of local intermediate inputs, so the bundle of intermediate inputs is imported from the rest of the world. Assuming zero profits, we have:

$$p_F = v a_v + p_I a_I,$$

where p_F is the price of the final good, a_v and a_I are the unit value added and input-bundle requirements, and v and p_I are the prices for value added and the input bundle.

[14]See Gil (2011) for a study of the interplay between formal and informal contracting in the context of the movie industry.

Suppose that the country under study is a small open-economy, so in an untaxed equilibrium, we have that p_F and p_I correspond to the world prices for these inputs. Now, consider the implications of levying ad-valorem import tariffs t_F on the final good, and t_I on the input bundle. Given the small-country assumption, the price of the final good will increase to $p'_F = t_F p_F$, while the price of the input bundle, will rise to $p'_I = t_I p_I$. Naturally, such protection will benefit local value added in that sector, which can see its remuneration rise. But, by how much? Holding a_v and a_I constant, it is straightforward to see that v can increase by:

$$\frac{v'}{v} = t_F + (t_F - t_I)\frac{p_I a_I}{v a_v}. \tag{C.1}$$

The effective rate of protection is thus higher than t_F provided that $t_F > t_I$, and is also increasing in the importance of inputs in production. As an example, if imported inputs are untaxed, and the ratio of value added to gross output is 1/2, as roughly observed in the data, the effective rate of protection is *twice* that implied by the tariff on final goods. Furthermore, it is straightforward to extend formula (C.1) to the case of multiple intermediate inputs indexed by s, facing heterogeneous tariffs levels:

$$\frac{v'}{v} = t_F + \sum\nolimits_s (t_F - t_s)\frac{p_s a_s}{v a_v}. \tag{C.2}$$

C.2 Baseline: A Simple Roundabout Model

Consider the effects of Home levying a vector of trade taxes $\mathbf{t} = (t_{1,\ldots,} t_S)$ that generate a wedge between domestic and world prices. Notice that tariff levels (and associated price wedges $p_s - p_s^*$) are the same regardless of whether the good is being imported as a final good or as an intermediate input. Maximizing $W(\mathbf{p}, \mathbf{p}^*)$ with respect to t_s yields:

$$\sum_{r=1}^{S}\left(\sum_{t=1}^{S}\frac{\partial \Pi_t(\mathbf{p})}{\partial p_r} + \frac{\partial S_r(p_r)}{\partial p_r}\right) \times \frac{\partial p_r}{\partial t_s} + \sum_{r=1}^{S}\left(\frac{\partial p_r}{\partial t_s} - \frac{\partial p_r^*}{\partial t_s}\right) \times m_r(\mathbf{p}) + \sum_{r=1}^{S}(p_r - p_r^*)\sum_{t=1}^{S}\frac{\partial m_r(\mathbf{p})}{\partial p_t} \times \frac{\partial p_t}{\partial t_s} = 0.$$

Noting that $\partial S_r(p_r)/\partial p_r = -c_r(p_r)$, and that:

$$\sum_{t=1}^{S}\frac{\partial \Pi_t(\mathbf{p})}{\partial p_r} = x_r(\mathbf{p}) - \sum\nolimits_{t=1}^{S} a_{rt} x_t(\mathbf{p}),$$

we can simplify the above expression to:

$$-\sum_{r=1}^{S}\frac{\partial p_r^*}{\partial t_s} m_r(\mathbf{p}) + \sum_{r=1}^{S}(p_r - p_r^*)\sum_{t=1}^{S}\frac{\partial m_r(\mathbf{p})}{\partial p_t} \times \frac{\partial p_t}{\partial t_s} = 0.$$

Next noting that goods market clearing imposes $m_r(\mathbf{p}) = -m_r^*(\mathbf{p}^*)$, we can further simplify this to:

$$\sum_{r=1}^{S} \frac{\partial p_r^*}{\partial t_s} m_r^*(\mathbf{p}^*) = \sum_{r=1}^{S} (p_r - p_r^*) \sum_{t=1}^{S} \frac{\partial m_r^*(\mathbf{p}^*)}{\partial p_t^*} \frac{\partial p_t^*}{\partial t_s},$$

which is equation (31) in the main text.

C.3 Tariffs on Final Goods and on Inputs in Competitive Economies

In this Appendix, we fill in the details of the competitive model with a final-good and input sector, other than the outside good sector 0. Sector F produces a good that is only consumed as a final good, while sector I produces a good that is only used as an input in production. In terms of the more general model in Section 6.2, this is simply a special case with $S = \{F, I\}$, $S_I(p_I) = 0$, and rent functions:

$$\begin{aligned} \Pi_F(p_F, p_I) &= (p_F - a p_I) x_F - \ell_F \\ \Pi_I(p_I) &= p_I x_I - \ell_I. \end{aligned}$$

Applying the formula in (31), and simplifying the system under the assumption that $\partial p_r^*/\partial t_s \neq 0$ for $s, r \in \{F, I\}$, we obtain:

$$1 = (t_F - 1)\varepsilon_{F,X}^* + (t_I - 1)\frac{1}{m_F^*(\mathbf{p}^*)}\frac{\partial m_I^*(\mathbf{p}^*)}{\partial p_F^*} \tag{C.3}$$

$$1 = (t_F - 1)\frac{1}{m_I^*(\mathbf{p}^*)}\frac{\partial m_F^*(\mathbf{p}^*)}{\partial p_I^*} + (t_I - 1)\varepsilon_{I,X}^*, \tag{C.4}$$

where $\varepsilon_{F,X}^*$ and $\varepsilon_{I,X}^*$ are the sectoral foreign export supply elasticities.

As is clear from these expressions, the presence of vertical linkages introduces a deviation or wedge relative to the standard formula linking sectoral optimal tariffs to sectoral inverse foreign export supply elasticities. What is the nature and sign of this wedge? To shed light on this, we first note that $m_F^*(\mathbf{p}^*) = c_F(\mathbf{p}^*) - x_F(\mathbf{p}^*)$ and $m_I^*(\mathbf{p}^*) = a x_F(\mathbf{p}^*) - x_I(\mathbf{p}^*)$ imply:

$$\begin{aligned} \frac{\partial m_I^*(\mathbf{p}^*)}{\partial p_F^*} &= a\frac{\partial x_F(\mathbf{p}^*)}{\partial p_F^*} \geq 0 \\ \frac{\partial m_F^*(\mathbf{p}^*)}{\partial p_I^*} &= -\frac{\partial x_F^*(\mathbf{p}^*)}{\partial p_I^*} \geq 0. \end{aligned}$$

Intuitively, other things equal, an increase in the world price in sector F increases input demand in the RoW, thus increasing the RoW's net imports of inputs. Similarly, an increase in the world input price decreases the return to final-good production, decreasing RoW final-good output, and thus increasing the net imports of final goods.

Having signed these cross-effects, we can now return to equations (C.3) and (C.4) and note that the manner in which vertical linkages affect optimal tariffs depends on subtle aspects of the environment. To see this, note that if the Home country is importing goods F and I, then

$m_F^*(\mathbf{p}^*) < 0$ and $m_I^*(\mathbf{p}^*) < 0$, and we necessarily have $t_F - 1 > 1/\varepsilon_{F,X}^*$ and $t_I - 1 > 1/\varepsilon_{I,X}^*$. The intuition is as follows: a final-good tariff provides the standard terms-of-trade gain, but in addition, by lowering the world price of the final good, it reduces the demand for intermediate inputs. This in turn reduces the world price of intermediate inputs, which affords an additional terms-of-trade gain, given that Home also imports inputs. Similarly, levying an import tariff on inputs not only affords the standard terms-of-trade gain, but the reduction in the world price of inputs, leads to an increase in the production of final-goods abroad, which reduces the world price of final goods as well, leading to an additional terms-of-trade gain when the Home country also imports final goods.

In sum, when Home imports both goods, vertical linkages lead to *higher* final-good tariffs and *higher* input tariffs than if these sectors were setting optimal tariffs based on the standard inverse-elasticity formula. Whether the wedge is higher or lower for final goods or for intermediates is less clear, however. With our assumption that inputs are used in fixed proportions, it turns out that $\partial m_I^*(\mathbf{p}^*)/\partial p_F^* = \partial m_F^*(\mathbf{p}^*)/\partial p_I^*$, and the model generates tariff escalation whenever: (i) inverse export supply elasticities are (weakly) higher for final goods than for inputs; and (ii) net imports of intermediate inputs are higher than net imports of final goods.

The above results rely, however, on Home importing both final-goods and inputs in the industry under study. If, for instance, Home is a net exporter of inputs, we have $m_I^*(\mathbf{p}^*) > 0$, and thus, as long as $t_F > 1$, equation (C.4) implies that we must have $(t_I - 1)\,\varepsilon_{I,X}^* < 1$, and because $\varepsilon_{I,X}^* < 0$, this implies $0 > t_I - 1 > 1/\varepsilon_{I,X}^*$. Thus, Home sets a *lower* export tax on inputs than it would do under the standard formula. Now, from equation (C.3), $t_I < 1$ and $m_F^*(\mathbf{p}^*) < 0$ imply $(t_F - 1) < 1/\varepsilon_{F,X}^*$, and thus Home also sets a *lower* import tariff on final goods whenever Home is a net exporter of inputs. The intuition is as follows: by levying an import tariff on final goods, Home reduces the world price of final goods, thereby reducing the demand for inputs in the RoW. This puts downward pressure on the world price of inputs, which constitutes a terms-of-trade loss for Home.

Following analogous steps, one can show that Home will also set a lower export tax on final goods and a lower import tariff on inputs whenever Home exports final goods and imports inputs. And, finally, when Home is a net exporter of both goods, it will choose to set higher export taxes on both goods than it would under the standard inverse elasticity formula.

The bottom line of all this discussion is that even in a simple world with just two goods and an outside sector, how vertical linkages affect the level of optimal tariffs very much depends on the pattern of trade.

C.4 Political Economy, Lobbying Competition and Tariff Escalation

The main result in Cadot et al. (2004) can be precisely formalized as follows. Suppose that the policy-maker envisions levying a tariff in only one sector s, so $p_r = p_r^*$ for all $r \neq s$. Then equation (34) simplifies to:

$$\frac{t_s - 1}{t_s} = \frac{\lambda}{\varepsilon_{s,M}} \frac{x_s - \sum_{t=1}^{S} a_{sr} x_r}{m_s},$$

and thus tariffs are higher the larger is λ, the lower the import demand elasticity $\varepsilon_{s,M} =$

$-(\partial m_s/\partial p_s)(p_s/m_s)$, and the larger the ratio of final-good sales relative to total imports in the sector (rather than the standard import penetration ratio, as in the literature without input-output links).

When the policy maker chooses positive protection in various sectors, matters become more complicated due to the second-best effect of tariffs working through tariff revenue. More specifically, when raising a tariff t_s, output x_r in sectors using x_s as an input will be depressed, which will tend to increase imports in those sectors and generate higher tariff revenue, a force that works against the model producing tariff escalation.[15] Indeed, this is precisely the mechanism that leads Gawande and Bandyopadhyay (2000) and McCalman (2004) to derive a positive effect of upstream tariffs on downstream tariffs in models in which lobbying is *only* carried out by downstream producers. These same authors, as well as Erbahar and Zi (2017) more recently, provide empirical evidence supporting the relevance of this *cascading* trade protection.

Despite these conflicting effects, Cadot et al. (2004) perform numerical simulations of a variant of this model, and they show that the cross-industry tariff revenue term in (34) is quantitatively small, and thus the model delivers implications consistent with data. Further empirical evidence consistent with a model of lobby competition with upstream and downstream sectors is provided in Gawande et al. (2012). Using tariff, trade and input-output data from 42 countries at different levels of development, Gawande et al. (2012) show that country- and sector-specific tariffs are decreasing in the extent to which that country-sector's output is used as an input in other sectors. Furthermore, taking into account counterlobbying forces, leads to estimates of λ that are higher than when estimating models without such counterlobbying, such as Grossman and Helpman (1994)'s "protection for sale" model (see Goldberg and Maggi, 1999). Intuitively, the standard model can only justify low tariffs via a low weight placed on lobbying contributions (which maps to λ above), and thus a higher weight on social welfare. Meanwhile, the model with input-output links is consistent with a higher value of λ leading to lower tariffs on account of counterlobbying forces, and thus the implied benevolence of the policy-maker is diminished.

C.5 Value Added Approach

Under the assumptions in the value added approach of Blanchard et al. (2016) outlined in Section 6.5, the sector-specific capital at Home and in Foreign now earn:

$$\begin{aligned}\Pi_F(p_F, p_{IFor}) &= p_F x_F - p_{IFor} x_{IFor} - \ell_F \\ \Pi_F^*(p_F^*, p_{IDom}^*) &= p_F^* x_F^* - p_{IDom}^* x_{IDom}^* - \ell_F^*,\end{aligned}$$

where x_{IFor} is the Foreign input used in Home production, and x_{IDom}^* is the Home input used in Foreign, and the corresponding prices for these inputs are p_{IFor} and p_{IDom}^*, respectively. For simplicity, we follow Blanchard et al. (2016) in assuming that these inputs are in fixed supply and

[15] One way to shut down these effects – implicitly invoked by Gawande et al. (2012)– is to assume that technology combines sector-specific capital and labor in fixed proportions. In such case, sectoral output is fixed and independent of input or output prices in any sector.

remain untaxed, so the income obtained from selling these inputs is a pure rent given by:

$$\begin{aligned}\Pi_I\left(p^*_{IDom}\right) &= p^*_{IDom}x^*_{IDom}\\ \Pi^*_I\left(p_{IFor}\right) &= p_{IFor}x_{IFor}.\end{aligned}$$

Welfare at Home is now given by:

$$W\left(\mathbf{p},\mathbf{p}^*\right)=1+\Pi_F\left(p_F,p_{IFor}\right)+\Pi_I\left(p^*_{IDom}\right)+S_F\left(p_F\right)+\left(p_F-p^*_F\right)\left(c_F\left(p_F\right)-x_F\left(p_F\right)\right),$$

where $\mathbf{p}=\left(p_F,p_{IFor}\right)$ and $\mathbf{p}^*=\left(p^*_F,p^*_{IDom}\right)$. Note that because inputs are in fixed supply, changes in the price of the Foreign input have no effect on Home's final-good production, and thus we can write this output as $x_F\left(p_F\right)$.

We next consider the effects of levying an import tariff t_F on the final good. Differentiating $W\left(\mathbf{p},\mathbf{p}^*\right)$ with respect to t_F and invoking $m_F\left(\mathbf{p}\right)=-m^*_F\left(\mathbf{p}\right)$ to simplify, delivers equation (35) in the main text, namely:

$$t_F-1=\frac{1}{\varepsilon^*_{F,X}}\left(1-\frac{p_{IFor}x_{IFor}}{p^*_F m_F}\xi_{For}-\frac{p^*_{IDom}x^*_{IDom}}{p^*_F m_F}\xi^*_{Dom}\right),$$

where $\varepsilon^*_{F,X}$ is the standard export supply elasticity, and ξ_{For} and ξ^*_{Dom} are positive terms.[16]

C.6 Trade Policy and Relational GVCs

In this Appendix, we overview work that has studied the implications and design of trade policy in environments with the distinguishing features of relational GVCs, namely, search frictions, customized production, and incomplete contracting. Do these features introduce novel reasons for trade policy intervention? And do they create new problems of global policy cooperation motivating international agreements with novel features?

To study these questions, we begin by considering a simple framework inspired by the work of Antràs and Staiger (2012a). We consider a three-country world with two "small" countries, Home and Foreign, and a large Rest of the World (RoW). This large RoW pins down the untaxed world price of a single homogeneous final good, which is used as the numéraire. Production of the final good requires a customized input x, and technology is summarized by a production function $y\left(x\right)$, with $y(0)=0$, $y'\left(x\right)>0$, $y''\left(x\right)<0$, $\lim_{x\to 0}y'\left(x\right)=+\infty$, and $\lim_{x\to\infty}y'\left(x\right)=0$. Home only produces final goods, while Foreign only produces intermediate inputs. The marginal cost of input production in Foreign (measured in terms of the numéraire) is constant and, through choice of the units in which inputs are measured, it is normalized to 1. This implies that the efficient level of input production x^E absent any market imperfections, trade taxes or other trade barriers is implicitly characterized by $y'\left(x^E\right)=1$.

It is assumed, however, that international contracts between suppliers and final-good producers

[16] More specifically, $\xi_{For}\equiv\frac{\left(\partial p_{IFor}/\partial t_F\right)\left(t_F/p_{IFor}\right)}{-\left(\partial p^*_F/\partial t_F\right)\left(t_F/p^*_F\right)}$ and $\xi^*_{Dom}\equiv\frac{-\left(\partial p^*_{IDom}/\partial t_F\right)\left(t_F/p^*_{IDom}\right)}{-\left(\partial p^*_F/\partial t_F\right)\left(t_F/p^*_F\right)}$.

are incomplete, and so the terms of trade between input suppliers and final good producers are determined by bargaining ex post after investments in input supply have already been sunk. For now, this is the only market friction we introduce. In particular, there is a unit measure of final-good producers at Home, and a unit measure of input producers in Foreign, and they are costlessly matched in pair. We shall consider environments with search frictions below.

We assume that each country can set trade taxes or subsidies on both the input and the final good. Because Foreign will never find it optimal to tax the final good, we can focus on the final-good tariff t_F^H at Home, defined in specific terms, and the input tariffs t_x^H and t_x^F set by Home and Foreign, also in specific terms. How do these instruments shape international exchanges? To explore this, note that domestic price of the final good at Home will be $1+t_F^H$, while the input tariffs will increase the marginal cost of delivering inputs from 1 to $1+t_x^H+t_x^F$. Recalling that the cost x of producing x units is sunk at the time the producer and supplier reach an agreement, the surplus these agents bargain over is given by:

$$S\left(x, t_F^H, t_x^H, t_x^F\right) = t_F^H y\left(x\right) - \left(t_x^H + t_x^F\right) x. \tag{C.5}$$

We take the extreme view that inputs are completely customized to final-good producers, and that final-good producers have no recourse to a secondary market, so that the breakup of a bargaining pair would result in a zero outside option for both producer and supplier. It would be straightforward to relax this assumption along the lines of Ornelas and Turner (2008) or Antràs and Staiger (2012a). In the bargaining, we assume that final-good producers obtain a share β of the surplus $S\left(\cdot\right)$ in equation (C.5), while suppliers obtain the remaining share $1-\beta$. Before they reach the bargaining stage, suppliers will then set a level of investment $\tilde{x}$ that solves:

$$(1-\beta)\left(1+\tau_1^H\right) y'\left(\tilde{x}\right) = 1 + (1-\beta)\left(t_x^H + t_x^F\right), \tag{C.6}$$

which implicitly defines $\tilde{x}(\tau_1^H, t_x^H, t_x^F)$. It is clear from (C.6) that $\tilde{x}$ is increasing in τ_1^H and decreasing in the sum of τ_x^H and τ_x^F. Intuitively, incomplete contracting leads to rent-sharing between the producer and supplier, and the latter's incentives to invest tend to be higher whenever the surplus from investment is higher, that is when τ_1^H is higher and when τ_x^H and τ_x^F is lower. Antràs and Staiger (2012a) show that the positive dependence of $\tilde{x}$ on τ_1^H and the negative dependence of $\tilde{x}$ on τ_x^H and τ_x^F hold for a variety of extensions of their framework featuring search frictions (see below), partial specificity, a secondary market for inputs, the existence of domestic input suppliers, two-sided holdup problems, and vertical integration, among others.

The result that input taxes – that is Home import tariffs on inputs or Foreign export taxes on inputs – reduce suppliers' investments is one of the key results in Ornelas and Turner (2008). They leverage this result and argue that trade liberalization, by reducing the holdup problem faced by suppliers leads to increases in trade flows that are above and beyond the standard increases in trade volumes predicted by models without contractual frictions.[17]

[17] Ornelas and Turner (2012) instead develop a framework in which input tariffs may ammeliorate the holdup

Although it is clear that final-good tariffs ameliorate the holdup problem while input tariffs aggravate it, it is not clear from equation (C.6) which trade policies will be socially efficient, and which ones will be unilaterally optimal from the point of view of the Home and Foreign governments. To answer these questions, one needs to take into account the effect of these policies on consumer surplus, producer surplus and tax revenue in each of the two countries. Antràs and Staiger (2012a) carry out such an analysis. They first show that an appropriate choice of input trade subsidies, combined with free trade in final goods, can fully resolve the international holdup problem and allow countries to attain the first-best. This is actually pretty straightforward to infer from equation (C.6). Note that setting $\tau_1^H = 0$ and $t_x^H + t_x^F = -\beta/(1-\beta)$, results in $y'(\tilde{x}) = 1$, and thus $\tilde{x} = x^E$. In sum, an appropriately chosen combination of input subsidies (provided by Home, Foreign or both) is sufficient to resolve the holdup problem, leaving no role for final-good tariffs to affect social welfare (remember that both Home and Foreign are small open economies).

Antràs and Staiger (2012a) next show that the Nash equilibrium policy choices of governments do not coincide with the internationally efficient policies, and they identify two dimensions of international inefficiency that arise under Nash policies. A first dimension is an inefficiently low input trade volume. Intuitively, input trade policy serves a dual role in this environment. On the one hand, as indicated above, subsidies to the exchange of intermediate inputs can help restore the volume of input trade toward its efficient level. On the other hand, input trade taxes can be used to redistribute surplus across countries, thereby shifting some of the cost of intervention on to trading partners.[18] A second dimension of inefficiency relates to the incentive of the Home government to also distort trade in the *final* good away from its free-trade level in order to reduce the domestic final good price and further shift bargaining surplus from foreign input suppliers to home final good producers.

Antràs and Staiger (2012a) then study the role of trade agreements in closing the gap between socially efficient and Nash equilibrium trade policy choices. Their key result is that the "shallow" focus on negotiations over market access advocated by the traditional terms-of-trade theory, is not effective in their setting. Instead, in the presence of bilaterally negotiated prices, effective trade agreements and the institutions that support them will have to evolve, from a market access focus toward a focus on deep integration, and from a reliance on simple and broadly-applied rules such as reciprocity and non-discrimination toward a collection of more individualized agreements that can better reflect member-specific idiosyncratic needs. These lessons very much resonate with the empirical results of Orefice and Rocha (2014) and Laget et al. (2020), documenting a relationship between the increased prevalence of deep integration (as measured by the number of policy areas covered in preferential trade agreements) and the rise of GVCs.[19]

problem of domestic suppliers. Intuitively, by raising the domestic price for a generic version of the goods they produce, an input can strengthen the bargaining power of suppliers and lead them to invest more.

[18] For instance, although an export tax may reduce the incentive of foreign suppliers to invest, these suppliers will be able to pass part of the cost of the tax on to Home final-good producers in their ex-post bargaining.

[19] Deep integration is often associated with provisions related to "behind-the-border" trade barriers such as competition policy, labor market regulation, consumer protection, environmental laws, movement of capital, or intellectual property rights protection.

Despite the above emphasis on holdup inefficiencies, Antràs and Staiger (2012b) clarified that the key aspect of the Antràs and Staiger (2012a) framework that delivers the need for "deeper" agreement is the fact that prices in international exchanges are not fully disciplined by market clearing conditions, and are instead bargained over. They further demonstrate that their main insights emerge in a much simpler framework without ex-ante investments but with search frictions in the matching between buyers and sellers. These matching frictions generate a lock-in effect that again leads to bargaining in international exchanges, with the resulting prices again not being fully disciplined by market clearing conditions.

The interplay between search frictions and trade policy takes a prominent role in the recent work by Grossman and Helpman (2020). Their framework shares some features with the work of Ornelas and Turner (2008), Antràs and Staiger (2012a) and Antràs and Staiger (2012b), but it is much richer in many dimensions, and it focuses on a different set of issues. The main goal of Grossman and Helpman (2020) is to study how input tariffs affect: (i) the incentives of final-good producers to search for suppliers in various countries; and: (ii) the bargaining between final-good producers and their various suppliers. In their framework, final-good producers assemble a bundle of intermediate inputs, and thus need to match with a continuum of suppliers. The productivity of these suppliers is in turn heterogeneous, but final-good producers do not learn that productivity until they are matched with a supplier. Because search costs are sunk in nature and the productivity of alternative matches is unknown, existing GVC relationships tend to be sticky in the model. As a result, relatively small unanticipated tariff changes do not lead to relocation of production, though in this case the tariffs can still cause contract renegotiations within existing matches due to the altered outside options of buyers in the presence of the tariffs. Large tariffs can overcome this stickiness and lead to the destruction of existing matches and the creation of new ones, either in the domestic economy or in other foreign countries.[20] The effects of input tariffs are ambiguous in their model and depend on various primitive parameters in rich ways, but numerical simulations of their model suggest that input tariffs are generally welfare reducing.

[20] Grossman and Helpman (2020) also provide suggestive evidence of these relocation effects following the recent imposition of tariffs (many of them on inputs) by the Trump administration.

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