Global Value Chains*

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September 17, 2021

Abstract

This paper surveys the recent body of work in economics on the importance of global value chains (GVCs) in shaping international trade flows and production patterns. On the empirical front, we begin by reviewing the "macro approach" to measuring the relevance of global production sharing in the world economy, while also offering a critical evaluation of the datasets (namely, World Input-Output Tables) that have been used to date to perform this value added accounting. We next discuss a "micro approach" that has instead employed firm-level datasets to document the ways in which firms have sliced up their value chains across countries. On the theoretical front, we propose an analogous dissection of the literature. First, we review a vast body of work developing country- and industry-level quantitative frameworks that are easily calibrated with World Input-Output Tables, and that shed light on the aggregate consequences of GVCs. Second, we overview micro-level frameworks that have treated firms rather than countries or industries as the relevant unit of analysis, and that have unveiled a number of mechanisms that are distinct from traditional models by which GVCs shape international trade flows. We close this survey with a discussion of a still infant literature on the desirability and effects of trade policy in a world of GVCs.

Keywords: Global value chains, trade in value added, positioning within GVCs, forward and backward GVC participation, macro models of GVCs, decentralized micro models of GVCs, lead firm models of GVCs, relational GVCs, GVCs and trade policy, tariff escalation.

JEL Classifications: F1, F2, F4, F6.

*We thank Rob Johnson for serving as discussant of our paper, and Emily Blanchard, Alessandro Borin, Lorenzo Caliendo, Rob Feenstra, and Michele Mancini for enlightening email exchanges. All errors are our own. The Online Appendix often mentioned in the main text is available at: http://scholar.harvard.edu/files/antras/files/antras_chor_gvc_chapter_online_appendix.pdf.

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1 Introduction

Since the early 1980s, the world economy has witnessed a significant transformation in the structure of international trade flows, giving rise to what some have called – in a somewhat Hobsbawm-like manner – the "Age of Global Value Chains" (Amador and Di Mauro, 2015; World Bank, 2020). This transformation was fueled by the combination of the information and communication technology (ICT) revolution, an acceleration in the rate of reduction in man-made trade barriers (via dozens of preferential trade agreements and China's accession to the WTO in 2001), and by political developments that brought about a remarkable increase in the share of world population participating in the capitalist system (Antràs, 2016). These forces worked in tandem to increase the extent to which firms used foreign parts and components in their production processes, as well the extent to which intermediate input producers sold their output internationally rather than to only domestic end-users. In fact, it has been estimated that trade in intermediate inputs constitutes as much as two-thirds of world trade (Johnson and Noguera, 2012). As a result, the typical "Made in" labels in consumer goods no longer do justice to the amalgam of nationalities that are represented in the value added embodied in these products.

This chapter will provide an overview of how the rise of global value chains (GVCs) has shaped and may continue to shape research in the field of international trade. To be clear, some aspects of this new wave of globalization are not entirely novel. In fact, previous chapters in the *Handbook of International Economics* have devoted specific subsections to trade in intermediate inputs, an important feature of GVCs. Nevertheless, with one notable exception to be discussed below, those *Handbook* chapters only briefly studied the robustness of standard results to the inclusion of tradable intermediate inputs, and did not elaborate on the distinctive predictions that arise when traded intermediate inputs are modelled.[1]

Our aim is instead to focus our attention on conceptual environments in which GVCs and intermediate input flows are salient, and to overview measurement techniques, empirical approaches, and theoretical frameworks specifically tailored to these environments. Our starting point will be a broad definition of GVCs, as "a series of stages involved in producing a product or service that is sold to consumers, with each stage adding value, and with at least two stages being produced in different countries" (see Antràs, 2020). According to this broad definition, a firm *participates* in a GVC if it contributes value in at least one stage in that GVC.

This broad definition is agnostic about the specific form in which foreign value added is embodied in production (e.g., raw materials, semi-processed inputs, or "tasks"). It is also consistent with various configurations of GVCs, including simple "spider-like" structures – in which multiple parts and components converge to an assembly plant that exports – and "snake-like" structures – in

[1] Section 3.1 of Jones and Neary (1984) discusses the complexities that arise in neoclassical trade theory when the commodity space is expanded to include intermediate inputs. That section also discusses the pioneering work of Sanyal and Jones (1982) and Dixit and Grossman (1982). Section 1.4 of Krugman (1995) studies the implications of traded and nontraded intermediate inputs for factor price equalization in models with increasing returns to scale. More recently, Costinot and Rodríguez-Clare (2014) provide a quantitative evaluation of the real income gains from trade in the presence of tradable intermediate inputs in Section 3.4 of their survey.

which value is created sequentially in a series of stages that can cross borders multiple times (see Baldwin and Venables, 2013). Similarly, this broad approach does not take a stance on whether trade transactions are initiated by exporters (as in Melitz, 2003), by importers, or by both. It is also consistent with complex GVCs designed and controlled by large "lead firms", and with more decentralized GVCs in which actors do not make production decisions pertaining to stages other than those in which they directly participate. Finally, this approach also encompasses a narrower definition of GVCs that emphasizes additional distinctive characteristics, namely that GVCs often entail the exchange of highly customized inputs on a repeated basis, with the contracts governing these relationships being incomplete and hard to enforce, features which often lead to non-trivial firm-boundary decisions (see World Bank, 2020; Antràs, 2020).

A recurring theme of this chapter will be to study how these different potential formalizations of GVCs add to our understanding of the determinants of international trade flows and production patterns. We will structure the chapter into five core sections. Sections 2 and 3 will review empirical work, Sections 4 and 5 will discuss theoretical contributions, and Section 6 will overview recent work on trade policy in a world of GVCs.

Within both the empirical and theoretical blocks of the chapter, we will distinguish between "macro" approaches and "micro" approaches. In what we refer to as "macro" approaches, the unit of analysis is a country or a country-industry, and the emphasis is on understanding the quantitative importance of GVCs both in determining international trade flows, but also in shaping the implications of trade policy shocks for aggregate income and for other macroeconomic variables. On the empirical front, this "macro" approach will be associated with the construction and manipulation of World Input-Output Tables to shed light on value added trade flows across countries and the implied degree to which production process have become globalized. On the theoretical front, this "macro" approach will focus on the development of structural interpretations of these World Input-Output Tables, with the ultimate goal of constructing more reliable tools for counterfactual analysis than those that ignore the relevance of GVCs in world trade.

In what we refer to as "micro" approaches, the unit of analysis will instead be the firm. Empirically, we will review a body of work that has studied GVC participation at the firm level, and that more broadly, has pushed the view that world trade flows are best understood as the aggregation of a large number of firm-level decisions related to the destinations to which firms export their products, the source countries from which they procure intermediate inputs, or the "platform" countries from which they assemble goods for distant destination countries. Theoretically, the "micro" approach is largely concerned with developing tools to solve the complex problems that firms face when designing their optimal global production decisions.

We close this Introduction with a brief note on the scope of this chapter. First and foremost, this is a survey written *by* academic economists *for* academic economists. This is of special relevance for a chapter on GVCs because this has been a subject of study in many social science disciplines and because there is a burgeoning policy literature on practical aspects of the governance of GVCs. Readers eager to get an interdisciplinary overview of academic work on GVCs can consult the recent

Handbook of Global Value Chains (Gereffi et al., 2019), while we refer readers interested in the policy aspects of GVCs to the recent World Development Report on *Trading for Development in the Age of Global Value Chains* (World Bank, 2020). A particularly engaging and accessible account of the rise of GVCs is provided in Baldwin (2016). Even within academic economics research, this chapter is almost exclusively focused on the implications of GVCs for the structure of international trade flows and real income. In doing so, we will not do justice to a growing literature studying the implications of GVCs for a broader set of macroeconomic phenomena related to shock propagation, synchronization of inflation, dampening of effects of exchange rate depreciation, or trade and current account imbalances (see Chapter 4 of World Bank, 2020). We also note that our survey complements and extends previous valuable overviews of theoretical and empirical work on GVCs, which include Feenstra (1998), Johnson (2018), Chor (2019), and Antràs (2020), among others.

Finally, and although we have noted above that the phenomenon of the rise of GVCs has been largely ignored in previous chapters of the *Handbook of International Economics* – the term "global value chain(s)" is in fact *not* mentioned in any of the chapters in previous volumes – there is certainly some overlap with Chapter 2 of the 4th volume of this *Handbook* (Antràs and Yeaple, 2014), which provided an overview of work on multinational activity. Indeed, Sections 5 and 7 of Antràs and Yeaple (2014) covered various aspects of the vertical expansion of multinational companies, which is an important manifestation of the rise of GVCs. To avoid duplication, we will refer readers to that chapter when quickly reviewing some work that could easily have been covered more extensively here under the umbrella of "global value chains". Due to space constraints, we have relegated many technical details to an Online Appendix.

2 Empirical Work: "Macro" Measurement

We start by surveying the literature on the "macro" measurement of GVCs, which has enabled researchers to gain an empirical handle on the importance of GVC activity in the aggregate. This measurement has improved because of developments on two fronts. On the conceptual front, key contributions have been made that clarify and expand on concepts in value added accounting; this has facilitated decompositions of the gross output and trade flows traditionally observed in the data into components that reflect input flows in GVCs. On the data front, economists have benefited from the yeoman's work that has improved and merged national accounts statistics into World Input-Output Tables, that record cross-country, cross-industry linkages in input use.

2.1 Accounting for Value Added

Consider the problem of a researcher interested in decomposing the ultimate sources of value added embodied in a good whose production has traversed multiple country borders (i.e., a GVC). When this good is observed in transit, one would typically only have information on its direct country source, but not the full set of countries and industries that contributed value added. In the absence of such details about the production process, the researcher might reasonably infer this from input sourcing patterns observed at a more aggregate level. This is precisely the type of information contained in World Input-Output Tables (WIOTs) that make it a key object of analysis for the "macro" measurement of GVCs. Inter-country or multi-region or world input-output tables – that extend domestic tables to incorporate multiple geographic units – are familiar objects for scholars of input-output analysis (see Miller and Blair, 2009, Chapter 3.3), and have more recently become a tool of necessity for economists studying GVCs.

We describe several leading approaches in value added accounting. Following Johnson (2018), we distinguish between decompositions of the value embodied in: (i) final goods (observed at their point of absorption into final use); and (ii) gross exports (which comprise flows of both final and semi-finished goods). Our purpose is not to present a comprehensive set of accounting identities, but rather to focus on conceptual issues, with an eye towards a discussion of some limitations to current "macro" measurement approaches.

We conduct this discussion around the WIOT as a core empirical building block. Consider an economic environment in which there are $J > 1$ countries and $S > 1$ industries. The *sub*scripts i and j index countries ($1 \leq i, j \leq J$); whenever a pair of subscripts is used (e.g., to describe a trade flow variable), the left subscript refers to the source country, while the right subscript refers to the destination country (so ij denotes a flow from i to j). The *super*scripts r and s index industries ($1 \leq r, s \leq S$); the left superscript refers to the source (or selling) industry, and the right superscript to the destination (or buying) industry.

Figure 1 illustrates the structure of a WIOT. At its center is a $JS \times JS$ matrix, $\mathbf{Z}$, whose typical entry Z_{ij}^{rs} is the value of inputs from industry r in country i (arrayed in the rows) that is purchased by industry s in country j (arrayed in the columns).[2] Note that we use bold characters to denote vectors or matrices, and un-bolded characters to refer to scalars. We will (somewhat inelegantly) refer to the unit of observation in either a row or column of Z_{ij}^{rs} as a "country-industry". The columns to the right of the $\mathbf{Z}$ matrix report the value of output from each country-industry that is instead absorbed in final-use (i.e., in consumption or investment). Define $\mathbf{F_j}$ to be the $JS \times 1$ vector that stacks the values F_{ij}^{r} of output from country-i, industry-r that is absorbed in country j for final-use, and denote the sum of these vectors over all destination countries by $\mathbf{F} = \sum_j \mathbf{F_j}$.[3] The accounting decompositions in this section treat $\mathbf{Z}$ and $\mathbf{F}$ as data objects taken as given from a WIOT. Moving beyond accounting though, it should be stressed that the WIOT entries should more properly be viewed as endogenous variables, that are the outcomes of firm-level decisions over how to optimally structure input sourcing and production processes. The "macro" models of GVCs we discuss in Section 4 will emphasize this perspective.

The starting point for most value added decomposition exercises is a basic gross output accounting identity. Let $\mathbf{Y}$ be the $JS \times 1$ vector of gross output values Y_i^r. Define $\mathbf{A}$ to be the $JS \times JS$ matrix of *direct requirement coefficients*, $a_{ij}^{rs} = Z_{ij}^{rs}/Y_j^s$, this being the value of the input in question (from industry r in country i) that is used in the production of \$1 of output (for industry s in country

[2]To be precise, Z_{ij}^{rs} is the entry in the $((i-1) \times J + r)$-th row and $((j-1) \times J + s)$-th column of the matrix $\mathbf{Z}$.
[3]More precisely, $\mathbf{F_j}$ is the column vector whose $((i-1) \times J + r)$-th entry is equal to F_{ij}^{r}.

Figure 1: The Structure of World Input-Output Tables

			Input use & value added							**Final use**			**Total use**
			Country 1			···	Country J			Country 1	···	Country J	
			Industry 1	···	Industry S	···	Industry 1	···	Industry S				
Output supplied	Country 1	Industry 1	Z_{11}^{11}	···	Z_{11}^{1S}	···	Z_{1J}^{11}	···	Z_{1J}^{1S}	F_{11}^{1}	···	F_{1J}^{1}	Y_1^1
		···	···	Z_{11}^{rs}	···	···	···	Z_{1J}^{rs}	···	···	···	···	···
		Industry S	Z_{11}^{S1}	···	Z_{11}^{SS}	···	Z_{1J}^{S1}	···	Z_{1J}^{SS}	F_{11}^{S}	···	F_{1J}^{S}	Y_1^S
	···	···	···	···	···	Z_{ij}^{rs}	···	···	···	···	F_{ij}^{r}	···	Y_i^r
	Country J	Industry 1	Z_{J1}^{11}	···	Z_{J1}^{1S}	···	Z_{JJ}^{11}	···	Z_{JJ}^{1S}	F_{J1}^{1}	···	F_{JJ}^{1}	Y_J^1
		···	···	Z_{J1}^{rs}	···	···	···	Z_{JJ}^{rs}	···	···	···	···	···
		Industry S	Z_{J1}^{S1}	···	Z_{J1}^{SS}	···	Z_{JJ}^{S1}	···	Z_{JJ}^{SS}	F_{J1}^{S}	···	F_{JJ}^{S}	Y_J^S
Value added			VA_1^1	···	VA_1^S	VA_j^s	VA_J^1	···	VA_J^S				
Gross output			Y_1^1	···	Y_1^S	Y_j^s	Y_J^1	···	Y_J^S	···			

j).[4] With matrix notation, gross output by country-industry can be expressed as:

$$\mathbf{Y} \;=\; \mathbf{F} + \mathbf{AY} \;=\; \mathbf{F} + \mathbf{AF} + \mathbf{A}^2\mathbf{F} + \ldots. \tag{1}$$

Gross output is thus the sum of value that is: (i) absorbed in final-use; and (ii) purchased for use as an input (across all buying country-industries). Iteratively substituting in this expression for $\mathbf{Y}$ into the right-hand side of this first identity yields the infinite sum representation in (1). The n-th term, $\mathbf{A}^n\mathbf{F}$ (where $n > 0$), is precisely the vector of gross output values that is absorbed in final-use after traversing exactly $(n+1)$ production stages, under the convention that each input- or final-use transaction counts as a single stage. It is worth recognizing at this juncture that (1) already entails modeling assumptions about technologies in this input-output system. In particular, there is a running assumption that the single set of direct requirements coefficients in $\mathbf{A}$ describes the production technology, both when the output is purchased as an intermediate input and when it is purchased for final-use; the same technology is used moreover regardless of the destination country to which that output is sold. This latter assumption has been called into question by de Gortari (2019), a criticism we will return to in Section 2.2.

The accounting in (1) adopts a "demand-driven" perspective, so termed because it traces the uses of the output of a given country-industry. An alternative – and complementary – approach instead focuses on the definition of gross output as the sum total of: (i) value added (i.e., direct payments by a country-industry to factors of production); and (ii) payments for intermediate inputs used in its production. Under this "supply-driven" perspective (Miller and Blair, 2009, Chapter 12), the corresponding gross output accounting identity can be written as:

$$\mathbf{Y} \;=\; \mathbf{V} + \mathbf{BY} \;=\; \mathbf{V} + \mathbf{BV} + \mathbf{B}^2\mathbf{V} + \ldots. \tag{2}$$

Here, $\mathbf{V}$ is the $JS \times 1$ vector that is the transpose of the row vector of value added entries, V_j^s, arrayed below the $\mathbf{Z}$ matrix in the WIOT (see Figure 1). $\mathbf{B}$ is the matrix of *allocation coefficients*, whose generic entry is given by $b_{ij}^{rs} = Z_{ij}^{rs}/Y_i^r$; this is the share of output in industry r in country i

[4] To be precise, the $((i-1)\times J + r)$-th entry of $\mathbf{Y}$ is equal to Y_i^r, while the entry in the $((i-1)\times J + r)$-th row and $((j-1)\times J + s)$-th column of $\mathbf{A}$ is a_{ij}^{rs}.

(i.e., the *source* country-industry) that is purchased as an input by industry s in country j.[5] In the infinite sum representation in (2), the term $\mathbf{B}^n\mathbf{V}$ $(n > 0)$ is thus the value of gross output accrued from primary sources of value added that enter into production exactly $(n+1)$ stages prior.

A familiar implication of (1) is that: $\mathbf{Y} = [\mathbf{I} - \mathbf{A}]^{-1}\mathbf{F}$, where $\mathbf{I}$ is the $JS \times JS$ identity matrix. In words, gross output can be computed by pre-multiplying $\mathbf{F}$ with the Leontief inverse matrix, $[\mathbf{I} - \mathbf{A}]^{-1}$ (Leontief, 1986). Somewhat less familiar is the fact that one can also obtain gross output via (2) as: $\mathbf{Y} = [\mathbf{I} - \mathbf{B}]^{-1}\mathbf{V}$. The matrix $[\mathbf{I} - \mathbf{B}]^{-1}$ is known as the Ghosh inverse, this being the analogue of the Leontief inverse constructed instead with the matrix of allocation coefficients (Ghosh, 1958).

2.1.1 Value Added In Final Goods

When a final good from industry s is observed in the country j where it is absorbed, it embodies value added that could have originated in any (or even all) of the JS country-industries in the world economy. Johnson and Noguera (2012) develop an approach for decomposing the ultimate sources of this value added. This is implemented by: (i) taking the vector $\mathbf{F_j}$ of final goods absorbed in country j; (ii) using the Leontief inverse $[\mathbf{I} - \mathbf{A}]^{-1}$ to back out the gross output needed to generate this final-use vector; and then (iii) pre-multiplying this by a vector of value added shares in gross output, $\hat{\mathbf{V}}\hat{\mathbf{Y}}^{-1}$, where the 'hat' notation denotes the diagonal matrix with the entries of the corresponding column vector arrayed along its main diagonal.[6] By computing:

$$\hat{\mathbf{V}}\hat{\mathbf{Y}}^{-1}[\mathbf{I} - \mathbf{A}]^{-1}\mathbf{F_j}, \tag{3}$$

this yields a vector whose $((i-1) \times J + r)$-th entry is the value added that originated from country i, industry r that is eventually absorbed in final-use in country j. Summing across all industries r and all destinations $j \neq i$, one obtains a measure of country i's *value added exports*, VAX_i, this being value added that originates from the country that is ultimately absorbed in the rest of the world. Johnson and Noguera (2012) propose examining how VAX_i compares against the country's gross exports (GX_i): Intuitively, this VAX_i-to-GX_i ratio reflects how involved the country is in direct versus indirect exporting through GVCs, providing an (inverse) measure of a country's engagement in cross-border production chains.

Two remarks are in order. First, one can further disaggregate the value added share of gross output V_j^s/Y_j^s (i.e., the diagonal entries of $\hat{\mathbf{V}}\hat{\mathbf{Y}}^{-1}$) into payments that accrue to distinct factors of production. This connects value added accounting to a vast preceding literature on factor content of trade accounting. On this front, Trefler and Zhu (2010) demonstrate how to implement an empirical test of the Vanek (1968) equations, suitably modified to a world with trade in intermediates, when the empirical researcher is armed with data from a WIOT.[7] More recently, Reshef and Santoni

[5] This is not to be confused with the direct requirements coefficient, which instead expresses the input value as a share of the gross output of the *destination* country-industry.

[6] The 'hat' notation will be used for a different purpose in Section 4 on macro models, to denote proportional changes under counterfactual scenarios.

[7] Earlier studies on the factor content of trade, such as Davis and Weinstein (2001), acknowledged that "some

(2019) implement an accounting decomposition of factor payments in a WIOT, to explore how much of the observed fall in the labor share of GDP can be explained by the rise of GVCs.

Second, the Johnson-Noguera approach traces value added through its *forward linkages* to final uses. An alternative would be to instead take the share of gross output absorbed by final demand in country j, $\hat{\mathbf{Y}}^{-1}\mathbf{F_j}$, and trace its *backward linkages* to sources of value added by pre-multiplying by $\hat{\mathbf{V}}[\mathbf{I}-\mathbf{B}]^{-1}$. While these may appear at first glance to be distinct approaches, one can show that: $\hat{\mathbf{V}}\hat{\mathbf{Y}}^{-1}[\mathbf{I}-\mathbf{A}]^{-1}\mathbf{F_j} = \hat{\mathbf{V}}[\mathbf{I}-\mathbf{B}]^{-1}\hat{\mathbf{Y}}^{-1}\mathbf{F_j}$.[8] In other words, one arrives at equivalent expressions for value added exports from adopting either a forward or backward linkages perspective.

2.1.2 Value Added In Gross Exports

A closely-related task is to unpack the sources of value added embodied in trade data that is observed "as-is", such as in a country's gross exports. This is in fact the task that the early GVC measurement literature embarked on: Hummels et al. (1998) and Hummels et al. (2001) posed this as a question of determining how much (as a share) of the value of a country's gross exports one can attribute to imported intermediate inputs. This well-known measure of "vertical specialization" (VS) – or the import content in exports – was arguably the first true measure of GVC participation, in that it captures trade flows involved in at least two border crossings.

Compared to the Johnson-Noguera VAX measure, efforts to decompose gross exports are by necessity more intricate. This is because gross exports (GX) comprise not just shipments of final goods, but also shipments of intermediate inputs that need to be carefully tracked in the accounting. This has given rise to an extensive line of work on gross export decompositions; see in particular Koopman et al. (2014) and Borin and Mancini (2019). The purpose of this subsection is not to provide an exhaustive taxonomy, but to instead draw out key conceptual issues from this work that a researcher should be alert to, in order to inform one's choices over which measures of trade in value added to use for a given research question.

Suppose that one is presented with the $S \times 1$ vector of country i's gross exports, $\mathbf{GX_i}$.[9] The schematic in Figure 2 below, adapted from Koopman et al. (2014), provides a useful organizing framework for decomposing sources of value added in these gross exports. At a high level, the dollar value recorded in $\mathbf{GX_i}$ is composed of content that is either of domestic or foreign origin. A first conceptual issue to pay attention to is that the domestic (respectively, foreign) content of exports is not equivalent to the domestic (respectively, foreign) value added embodied in gross exports. In an age of active trade of goods-in-process within GVCs, the value added contained in a particular input is recorded in country i's gross exports multiple times ("double-counting") if it is shipped through i more than once over the course of production. As an example, suppose that iron ore mined in Canada is exported to the US for fabrication into a car chassis; that chassis is

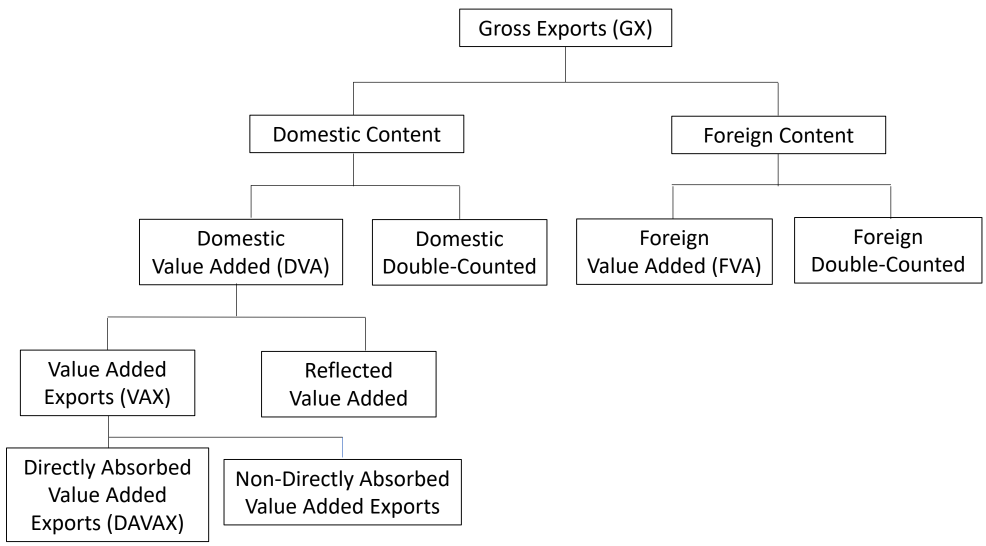
error surely arises from the fact that we have assumed that intermediates used in the production of exportables are all of national origin" (p.1444), but did not tackle this issue head-on due to data limitations. See Reimer (2006) for an effort at factor content accounting with trade in intermediates in a low-dimensional setting.

[8]This follows from the property that the direct requirements and allocation matrices are related by: $\mathbf{B} = \hat{\mathbf{Y}}^{-1}\mathbf{A}\hat{\mathbf{Y}}$.

[9]From a WIOT, the r-th entry of $\mathbf{GX_i}$ can be computed as: $\sum_{j\neq i}\sum_s Z^{rs}_{ij} + \sum_{j\neq i} F^r_{ij}$.

then shipped back to Canada for final assembly, before the finished car is ultimately purchased by a household in the US. The Canadian value added in the original iron ore would be counted twice in Canada's gross exports, the second time as part of the finished car. Intuitively then, how much value added gets double-counted will depend on the extent to which the country is a hub for GVCs, with goods-in-process routed through it multiple times.[10] This breakdown of domestic (respectively, foreign) content into a pure value added component and a double-counting piece is illustrated in the second level of the schematic.

Figure 2: Decomposing Sources of Value Added in Gross Exports



It is instructive to dive into how the domestic value added (or DVA) embodied in a country's exports can be computed (less the double-counting term), by drawing on the forward linkage approach laid out in Section 2.1.1. Define $\mathbf{DVA}_i$ to be the $S \times 1$ vector whose r-th entry is the value added in country-i, industry-r exports that originates from domestic (i.e., country i) sources. $\mathbf{DVA_i}$ can then be computed as: $\mathbf{\hat{V}_i \hat{Y}_i^{-1}[I - A_{ii}]^{-1}GX_i}$, where $\mathbf{A_{ii}}$ is the $S \times S$ matrix block of direct requirements coefficients that corresponds to purely domestic input-output transactions. This expression for $\mathbf{DVA_i}$ is reminiscent of (3): One uses the Leontief inverse of $\mathbf{A_{ii}}$ to compute the sum of purely domestic sources of gross output – that has not crossed borders at any stage of production – that go into generating the gross export vector $\mathbf{GX_i}$. The domestic value added $\mathbf{DVA_i}$ is then extracted from $\mathbf{[I - A_{ii}]^{-1}GX_i}$ by pre-multiplying it by $\mathbf{\hat{V}_i \hat{Y}_i^{-1}}$, the diagonal matrix of value added shares in each industry in country i. For the country as a whole, domestic value added in exports

[10] Although double-counting could be a significant phenomenon in some specific cross-border production chains, it turns out to be relatively small in the aggregate at the country level. In the World Input-Output Database (2013 release), when summing across the years 1995-2011, double-counting never constitutes more than 2% of the domestic content of exports for each country; the largest shares recorded are by the rest of the world (1.8%), Germany (1.5%), and China (0.9%). Similarly, the countries with the highest double-counting shares in the foreign content of their exports are: Germany (1.7%), the rest of the world (1.7%), and China (1.2%). Calculations based on the Chapter 1 dataset of the World Development Report (World Bank, 2020).

(DVA_i) is simply the column sum of $\mathbf{DVA_i}$.

Two properties of domestic value added in exports make it a concept of particular interest. First, the non-domestic value added share of gross exports, $(GX_i - DVA_i)/GX_i$, is precisely equal to the VS measure – the import content in exports – formulated by Hummels et al. (2001); see Johnson (2018) for this result in a two-country case, and Borin and Mancini (2019) for a more general proof. Second, Los et al. (2016) show that DVA_i is equal to the decrease in country i GDP that would be implied by the input-output system if exports of country i to the rest of the world – both of intermediate inputs and final goods – are shut down, holding all other entries of the WIOT constant. Such a counterfactual shift is not easy to rationalize in a fully-specified model with general equilibrium adjustments. But this "hypothetical extraction" approach nevertheless provides an intuitive interpretation for DVA_i, as well as a convenient calculation method.

Is domestic value added (DVA) in exports then also equivalent to value added exports (VAX) from Johnson and Noguera (2012)? The answer is no, as pointed out by Koopman et al. (2014). This is because DVA in general contains domestic value added that eventually gets "reflected" back and absorbed in final uses in the home country, as shown in the third layer of the Figure 2 schematic. (Using the stylized GVC example from above, US value added embodied in its chassis exports to Canada is reflected back in the assembled car purchased by a US household.) Naturally, the gap between DVA and VAX is likely to be larger for countries engaged in GVCs with a lot of to-and-fro trade across borders in parts and components, such as in the model of Yi (2010), and that also absorb a significant amount of the finished goods back in their domestic economies.[11]

The final layer in Figure 2 breaks down VAX into two further components. As shown by Borin and Mancini (2019), one can track the part of VAX that crosses exactly one country border ($DAVAX$, or "directly absorbed" VAX): this comprises value added that is immediately absorbed in final use in its first destination country, or that is used as an input in production processes contained entirely in that country. The difference between gross exports and $DAVAX$ is value which makes at least two border crossings, and can be regarded as trade flows involved in GVCs. Borin and Mancini (2019) therefore propose $(GX - DAVAX)/GX$ as a measure of the share of "GVC trade" in gross exports. This in turn can be written as the sum of two pieces: a first that captures forward GVC participation, given by $(DVA - DAVAX)/GX$, this being domestic value added in exports that is used abroad and then re-exported; and a residual term $(GX - DVA)/GX$, which one can interpret as capturing imported content from backward GVC participation.

Before turning to patterns in the data, we highlight a subtle issue that emerges if one is seeking to decompose gross exports at levels of aggregation more detailed than the country level (such as bilateral, industry, or country-by-industry trade flows).[12] One might imagine that this amounts to breaking gross exports down into finer terms, and assigning these to appropriate country or industry

[11] This characterization is broadly consistent with the data: the reflected share of domestic value added is largest for the US (8.6%), the rest of the world (5.5%), and Germany (3.0%), over 1995-2011 in the World Input-Output Database (2013 release).

[12] See for example Wang et al. (2013). Los and Timmers (2018) take a different approach to this question by focusing on value added exports at the bilateral level.

bins. As it turns out, a consequence of double-counting is that there is not a unique way to perform this assignment. A modified version of the car GVC example will help to clarify this: Suppose the iron ore from Canada is first exported to Mexico (rather than the US) to produce the chassis; this is then exported back to Canada for assembly, after which the car is finally sold in the US. One could either label the value added in the initial iron ore exports to Mexico as DVA, with that same content in Canada's exports of the finished car to the US labeled as double-counting, or vice versa. This distinction clearly does not matter if we are decomposing gross exports for Canada as a whole. However, when the trade flow of interest is bilateral, industry or country-industry exports, the value added would be classified as DVA in mining exports to Mexico and as double-counting in motor vehicle exports to the US under the former approach; under the latter convention, the DVA and double-counting labels would instead be switched around. The upshot is that gross export decompositions at these more detailed levels – if consistently performed – require that one specify an accounting convention. There are two natural choices here: a *source-based* approach, where the value added is labeled as DVA the first time it exits the country (and is treated as double-counting thereafter); or a *sink-based* approach, where the value added is instead labeled as DVA the final time it exits the country's borders (Nagengast and Stehrer, 2016; Borin and Mancini, 2019).

2.1.3 "Macro" Trends in GVC Activity

We illustrate several broad trends in GVC activity in recent decades, using measures that build on the above value added accounting methodologies. The underlying data we draw on are from the 2013 release of the World Input-Output Database (WIOD).[13] This provides annual observations for 35 industries and 41 countries (including a rest-of-the-world aggregate) from 1995-2011.

We examine four measures of the prevalence of GVC activity in international trade flows. These are: (i) the VS measure of Hummels et al. (2001), given by $(GX - DVA)/GX$; (ii) the ratio of value added to gross exports, VAX/GX, as proposed by Johnson and Noguera (2012); (iii) the share of GVC trade in gross exports, $(GX - DAVAX)/GX$, from Borin and Mancini (2019); and (iv) the share of GVC trade in domestic value added in exports, $(DVA - DAVAX)/DVA$. This last measure is one we suggest as a close counterpart to (iii); by replacing GX with DVA, we remove the foreign content and domestic double-counting terms from gross exports, before assessing the importance of domestic value added that crosses more than one border.

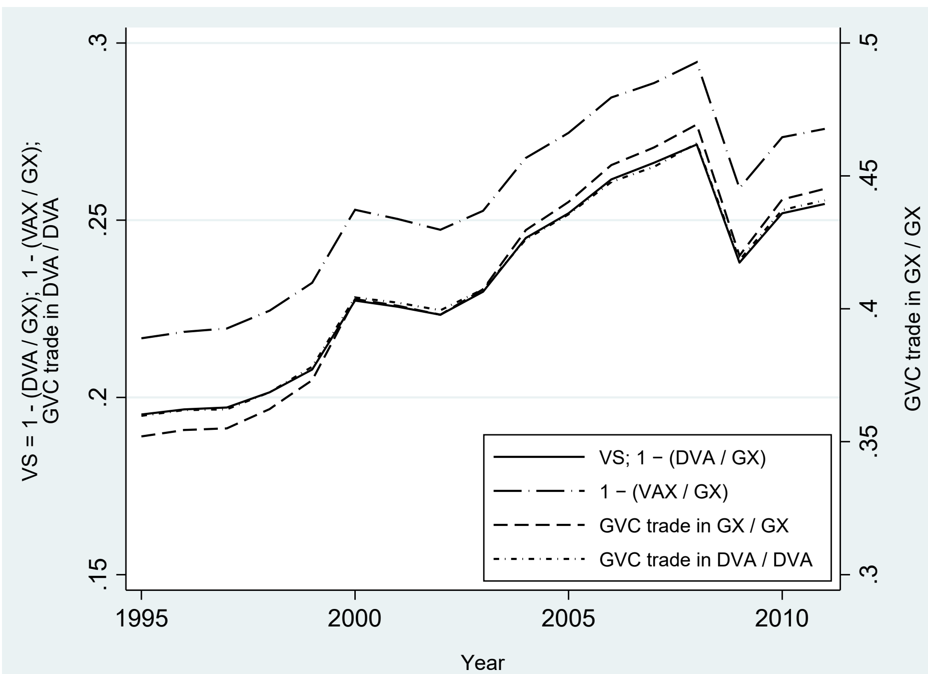
The respective numerators of (i), (iii) and (iv) capture trade flows involved in multiple border crossings; these three measures are thus increasing in the extent to which production is conducted within GVCs. On the other hand, the Johnson-Noguera VAX/GX ratio in (ii) is an inverse measure of GVC activity, since gross exports exceed VAX by a greater extent when there is more indirect trade involving intermediate inputs. In the illustration below, we therefore subtract VAX/GX from 1, to obtain a measure that would in principle correlate positively with (i), (iii) and (iv). Note that

[13] More specifically, we use the WIOD gross export decomposition data from Chapter 1 of the World Development Report (World Bank, 2020), available at: http://pubdocs.worldbank.org/en/834031570559525797/Chapter-1.zip. This is performed at the country-by-industry-by-year level with source-based accounting for double-counting terms.

we do not separately plot the ratio of domestic value added in gross exports (DVA/GX), which Koopman et al. (2014) have emphasized in their work; this is because (as remarked earlier) the VS measure in (i) is exactly equal to $1 - DVA/GX$ at the country level.

Figure 3 displays these measures of GVC activity computed at the world level.[14] The tight correlation (>0.99) between any pair of these measures is striking, at least at this broad level of aggregation. This paints a uniform message about trends over time, regardless of one's preferred measure: Cross-border GVC activity rose steadily from the mid-1990s until the late 2000s. Looking across the measures, the import content in exports (VS) increased from 0.20 in 1995 to 0.27 in 2008. Although there is a small gap between $1-(VAX/GX)$ and $VS = 1-(DVA/GX)$ due to the exclusion of reflected trade from VAX, both measures display an essentially identical time trend. Similarly, the share of gross exports associated with GVC trade, $(GX - DAVAX)/GX$, rose from 0.35 in 1995 to a peak of 0.47 in 2008 (right vertical axis). When we instead examine the share of domestic value added in exports that crossed multiple borders, $(DVA - DAVAX)/DVA$ in (iv), the time pattern is preserved while the average share falls to a level comparable to the VS and $1-(VAX/GX)$ measures (left vertical axis).

Figure 3: GVC Trade over Time



The above patterns echo the findings of Johnson and Noguera (2017). Their estimates of the VAX/GX ratio, constructed off input-output tables from past decades, indicate that this rising engagement in GVCs commenced as early as the 1970s, with a sharp acceleration from 1990-2008. The global financial crisis marked a halt and even a slight reversal in GVC activity, as evident too

[14]We first sum up GX, DVA, VAX, and $DAVAX$ respectively across all country-industries in a given year, and then compute the measures defined in (i)-(iv).

from Figure 3. This coincided with the onset of a widely-documented slowdown in the growth of world trade as a share of GDP, as highlighted for example in the World Economic Outlook IMF (2016) or by Chart 1 in Antràs (2020). Why GVC participation appears to have ebbed is a topic that warrants more study, particularly as newer years of WIOT data become available. An interesting question will be whether there are common underlying drivers, such as a weak recovery in global demand or rising trade frictions, that simultaneously explain both the slowdown in trade as a share of GDP and in GVC trade as a share of exports.

We conclude this subsection by highlighting a number of key applications. Notably, measures of trade in value added have prompted reappraisals of several international macroeconomic phenomenon. The magnitude of prominent trade imbalances is considerably smaller – in the case of the U.S.' trade deficit with China, by about one-third – when assessed in value added rather than gross terms (Johnson and Noguera, 2012; Koopman et al., 2014). On a related note, the classic question of how exchange rate movements affect the competitiveness of a country's exports needs to take into account the growing use of imported inputs in a GVC world. This has led to proposals to update how country real effective exchange rates (REERs) are constructed, to incorporate information on value added exports when weighting across trade partners' exchange rates (Bems and Johnson, 2017; Patel et al., 2019).

Researchers have also applied these GVC measures to shed light on how countries' participation in GVCs is related (at least at an empirical level) to the economic fundamentals that drive patterns of specialization and comparative advantage. The wide-ranging regressions in Fernandes et al. (2020) uncover how traditional determinants of trade flows – factor endowments, institutions, geography, trade policy – correlate well with backward and forward GVC participation (as per the measures proposed by Borin and Mancini, 2019). This is often over and above their role in explaining gross exports, though causal interpretation is limited by the familiar challenge of finding good instrumental variables in cross-country settings. More reassuring from the standpoint of identification, Fernandes et al. (2020) further exploit cross-industry variation (following Romalis, 2004) to show that the interaction between country factor endowments and industry factor intensities explains patterns of participation in GVCs. This echoes Ito et al. (2017), who present similar evidence that Heckscher-Ohlin forces are relevant for understanding value added exports.

It is important to acknowledge here a large body of policy-oriented work that has used these measures of GVC activity to study their consequences for developmental outcomes. Toward this end, the 2020 World Development Report highlights how GVC participation is associated with higher growth in GDP per capita and labor productivity, gains in poverty reduction, more transfer of skills, as well as employment creation that often benefits the female workforce (see Chapter 3, World Bank, 2020). While these correlations are striking, more remains to be done to establish the causal nature of these relationships.[15] Moreover, these empirical patterns should ideally motivate theoretical work to clarify the mechanisms that link GVCs with macro outcomes such as economic

[15] Altomonte et al. (2018) provides one such effort at bridging this causality gap: They propose an instrumental variable based on the availability of port locations that can accommodate mega-container ships; this is shown to predict well a country's DVA in exports, which in turn is positively linked with growth in income per capita.

growth. Modeling work along these lines is exceedingly limited at this point; Sposi et al. (2021) are a welcome exception seeking to sort through the interplay between countries' participation in GVCs and the process of physical capital accumulation.

2.2 Critical Assessment: Limitations and Directions for Improvement

The quality of the "macro" measures of GVC participation just described hinges on the reliability of the information in the underlying WIOT. Researchers have thus benefited from concerted efforts over the past decades to advance the construction of WIOTs; see for example the 2013 symposium on this topic in *Economic Systems Research*. We briefly discuss ongoing methodological challenges and limitations, as well as potential directions for improvement.

At the expense of stating the obvious, the construction of WIOTs – by such initiatives as the GTAP, OECD-ICIO, Eora, and WIOD – is an extensive undertaking, to harmonize and merge domestic input-output tables for many countries. The key substantive challenge here is how to credibly populate the off-diagonal block entries of a WIOT, that relay the crucial information on cross-country, cross-industry linkages. From domestic tables, what one observes is the value of imports by country-j, industry-s of goods from industry-r, but aggregated across source countries, that is respectively: (i) used as an input, $\sum_{i\neq j} Z_{ij}^{rs}$; and (ii) absorbed in final-use, $\sum_{i\neq j} F_{ij}^{r}$. To then apportion these flows across source countries i, the standard approach is to adopt proportionality assumptions; these take the form: $\tilde{Z}_{ij}^{rs} = \omega_{ij}^{r} \sum_{i\neq j} Z_{ij}^{rs}$ and $\tilde{F}_{ij}^{r} = \omega_{ij}^{r} \sum_{i\neq j} F_{ij}^{r}$, where the ω_{ij}^{r}'s are suitably chosen weights. For example, Johnson and Noguera (2012) set ω_{ij}^{r} equal to the share of imports from i in country j's total industry-r imports, while Trefler and Zhu (2010) express these imports as a share of j's absorption (output less net exports) in industry r.[16]

More recent WIOTs have sought to improve on this standard methodology, with a key step being to construct different proportionality weights ω_{ij}^{r} for flows of imported intermediates and final goods respectively. This has been achieved by bringing in the UN Broad Economic Categories (BEC) classification, together with detailed product-level trade flows, to distinguish between imported products that are intermediates versus final goods. The WIOD (Dietzenbacher et al., 2013), the OECD-ICIO (Koopman et al., 2014), as well as the most recent GTAP editions (Carrico et al., 2020) have each implemented this approach.[17] While clearly an improvement, note that a common set of ω_{ij}^{r} weights continues to be applied to imports of inputs across all purchasing industries s in country j; in other words, the source-country shares of automobile products purchased by say the Automobile manufacturing industry would be identical to that purchased by the Transportation services industry. Moreover, direct information on the composition of imports of services by end-uses is even more challenging to obtain, which necessitates further assumptions.

[16] In the context of the factor content of trade literature, Puzzello (2012) argues that such proportionality assumptions do not appear to generate a large bias if the purpose is to decompose the content of *net* trade.

[17] This modification to the proportionality assumptions appears to result in some meaningful adjustments to measures of GVC participation. See for example Figure 2 in Timmer et al. (2015), which compares country-level VAX/GX ratios computed from different leading WIOT databases. Slightly larger gaps emerge between the measures calculated from the WIOD and those from Johnson and Noguera (2012), with the gaps more noticeable among countries with low VAX/GX ratios that are in principle most engaged in GVCs.

Building on the above, we highlight several potential directions for improvement in macro measurement. First, we anticipate and welcome efforts to bring to bear detailed micro data to further refine the construction of proportionality weights. There is already work along these lines: The IDE-JETRO's Asian International Input-Output (AIIO) Tables uses proprietary firm-level surveys from several Asian countries, specifically the information gathered on the composition of firm imports, to construct weights ω_{ij}^{rs} that vary further by the identity of the purchasing industry s (Meng et al., 2013). Such work is likely to advance with empirical efforts to merge administrative data on firm operations with customs data on firm-level trade transactions, as the resulting databases would be directly informative of the ω_{ij}^{rs} weights. Using a combination of Chinese customs and manufacturing survey data, Kee and Tang (2016) document an increase in the domestic value added in Chinese firms' exports during 2000-2007.[18] Bems and Kikkawa (2021) work with a very rich Belgian data environment that allows them to observe not only firms' cross-border purchases, but also their domestic transactions in sales tax records. Their findings suggest that the use of sectoral aggregates in WIOTs leads to an over-statement of trade in value added, as this overlooks heterogeneity in input sourcing patterns across large versus small firms. Given the high data requirements, existing studies that incorporate firm-level data to improve value added accounting are limited in geographic coverage. There remain significant hurdles to linking such micro datasets across countries – including concerns over firm confidentiality – though this may eventually become feasible in regions with a history of collaboration among national statistical agencies (e.g., the EU).

A second distinct data challenge is raised by the presence of multi-product firms (Bernard et al., 2010, 2011). Large and more productive firms that tend to select into GVC participation are also more likely to manufacture and export multiple products. Even if one were armed with detailed data on such firms' imported intermediates, one would still require information on how these inputs are split across the manufacturing processes for different products in order to perform an accurate accounting of value added flows. Such information is as of now not routinely collected in firm surveys or manufacturing censuses. While one might hypothesize that this concern could be alleviated with access to even finer establishment-level microdata – as establishments could be more specialized in their product scope – it has been documented that multiproduct firms often feature multiproduct establishments (see for example Boehm et al., 2018, in the context of India).

A third measurement issue is raised by de Gortari (2019), who documents how observed patterns of input sourcing can differ substantially across firms within the same industry, depending on the identity of the export market a firm's output is destined for. Using Mexican customs data, de Gortari (2019) shows that motor vehicle firms in Mexico whose main export market is the US (respectively, Germany) bring in a disproportionate share of their imported inputs from the US (respectively, Germany). This is not taken into account by standard approaches, which impose a uniform set of input-output coefficients for the entire Mexican motor vehicle industry. As a practical consequence,

[18] A related strand of work instead disaggregates country input-output tables by using computational algorithms subject to adding-up constraints, in order to distinguish between the input sourcing patterns of key subsets of firms. Koopman et al. (2012) use this approach to explore differences across processing versus ordinary trade firms in China, while Tang et al. (2020) examine variation across state- versus private-owned enterprises.

this understates the extent of GVC trade between the US and Mexico in this industry, and implies lower welfare costs should a US-Mexico tariff war disrupt cross-border value chains. Addressing this shortcoming ultimately requires better measurement, specifically firm-level data that would allow the statistician to observe input sourcing patterns across GVCs that (at a minimum) are distinguished by their immediate export destinations. The criticism that de Gortari (2019) levies is at heart also conceptual in nature, as it draws attention to the embedded assumption in standard accounting approaches that global production can be summarized by a single roundabout technology matrix.[19] It thus bears repeating that value added accounting is ultimately *not* free of modeling assumptions about the structure of production.

Last but not least, measures of GVC trade constructed under current methodologies are available only with a significant lag. This is because domestic input-output and supply-use tables are typically only released at benchmark intervals (say, five years).[20] These macro measures are thus ill-suited for delivering insights into how GVC activity is evolving in real-time over the business cycle. This is unfortunate, given that the demand for such insights has grown with the supply chain disruptions seen during the U.S.-China tariff war and the Covid-19 pandemic. A related limitation is that the industry categories in existing WIOTs are fairly broad (e.g., "Electrical and Optical Equipment"), and so do not shed direct light on GVCs for more specific goods of interest (e.g., "semiconductors"). Filling these gaps will require higher-frequency and more detailed data; toward this end, a potential direction would be to harvest information on vessel movements or container processing at ports, to more directly track shipments within supply chains (see for example, Cerdeiro et al., 2020).

2.3 Measures of Positioning in GVCs

Apart from quantifying the size and share of GVC trade flows, researchers have also taken an interest in the positioning of countries and industries within GVCs. We discuss here a class of measures that provide a formal basis for statements about whether a country is specialized in relatively upstream activities or is more proximate to final demand. Such notions of production staging feature prominently in economic models of GVCs (see Sections 4 and 5). For example, the positioning of countries within GVCs can be shaped by fundamentals such as productivity (Costinot et al., 2013) or geography (Antràs and de Gortari, 2020).

In the setting of a WIOT, each country-industry is traversed as a stage in many production chains that originate in primary sources of value added and terminate when the finished goods or services are absorbed in final use. We distinguish between two production staging concepts. The first captures the average positioning of a country-industry in its "upstreamness" relative to final demand (i.e., consumption or investment). The second measure instead gauges the country-industry's "downstreamness" in relation to sources of value added (i.e., labor and other factors).

[19]de Gortari (2019) formulates this as an assumption that production in GVCs is represented as a first-order Markov chain, when this should instead be viewed as a higher-order Markov chain.

[20]WIOTs that are constructed on a yearly basis, such as the WIOD and Eora, typically estimate the entries in non-benchmark years, taking guidance from other national accounts data that are reported at an annual frequency. The construction of the Eora in particular makes extensive use of imputation algorithms (see Lenzen et al., 2013).

The measure of "upstreamness" builds on the forward linkage decomposition presented earlier in equation (1). Since the n-th term, $\mathbf{A}^{n-1}\mathbf{F}$, in (1) is the vector of gross output that traverses exactly n stages to reach final demand, it is natural to multiply the $\mathbf{A}^{n-1}\mathbf{F}$ term by n and compute:

$$\mathbf{F} + 2\mathbf{AF} + 3\mathbf{A}^2\mathbf{F} + \ldots \;=\; [\mathbf{I} - \mathbf{A}]^{-2}\mathbf{F}. \tag{4}$$

The "upstreamness", U_i^r, of country-i, industry-r is then defined as the $((i-1) \times J + r)$-th entry of (4) divided by Y_i^r.[21] Intuitively, U_i^r is a weighted-average of the number of production stages that this country-industry's output takes to arrive at final demand, where the weights are equal to the shares of that gross output that crosses exactly n stages before absorption in final uses. Note that $U_i^r \geq 1$, and that the minimum value of 1 is attained if and only if the entirety of output, Y_i^r, is absorbed directly in final demand. Moreover, U_i^r is larger when a greater share of Y_i^r is purchased as an intermediate input, and particularly so when multiple stages are still needed before the point of final demand is reached.

This upstreamness measure has several interesting properties. Fally (2012) and Antràs et al. (2012) show that the set of U_i^r's constructed in this manner is also the unique solution (up to a normalization) to the recurrence relation: $\mathbf{U} = \mathbf{1} + \mathbf{BU}$, where $\mathbf{U}$ is the column vector that contains U_i^r as its $((i-1) \times J + r)$-th entry. (Here, $\mathbf{1}$ is a column vector of 1's, while $\mathbf{B}$ is the matrix of allocation coefficients b_{ij}^{rs}.) Each country-industry can thus be viewed as being one stage more upstream than a weighted-average of all country-industries that purchase inputs from it. This provides an alternative foundation for U_i^r as a measure of stage distance to final demand. A quick matrix manipulation moreover yields: $\mathbf{U} = [\mathbf{I} - \mathbf{B}]^{-1}\mathbf{1}$, so that U_i^r is equal to the sum of the entries in the $((i-1) \times J + r)$-th row of the Ghosh inverse matrix, $[\mathbf{I} - \mathbf{B}]^{-1}$. This establishes a further equivalence, between U_i^r and the concept of total forward linkages (Jones, 1976): U_i^r is also equal to the increase in costs that would be transmitted to total gross output in the world economy as a result of a unit increase in payments to primary factors in country-i, industry-r.

The measure of "downstreamness" from primary sources of value added is constructed in an analogous fashion by working with the backward linkage decomposition of gross output in equation (2). Multiplying the n-th term in (2) by n, we have:

$$\mathbf{V} + 2\mathbf{BV} + 3\mathbf{B}^2\mathbf{V} + \ldots \;=\; [\mathbf{I} - \mathbf{B}]^{-2}\mathbf{V}. \tag{5}$$

The "downstreamness", D_j^s, of country-j, industry-s from primary factors is defined as the $((j - 1) \times J + s)$-th entry of (5) divided by Y_j^s. D_j^s is thus a weighted-average of the number of stages traversed from primary factors to produce output in country-j, industry-s, where the weights are the shares of gross output that accrue from value added that has crossed exactly n stages. Note

[21] In practice, one needs to account for the value of net inventories N_i^r reported for each country-industry in a typical WIOT. The standard approach is to adopt a proportionality assumption, that the breakdown of uses of inventories across both intermediate and final use is identical to that for non-inventorized output for each country-industry. Antràs and Chor (2019) show that this implies a correction procedure – multiplying each Z_{ij}^{rs} and F_{ij}^{rs} term in the WIOT by $Y_i^r/(Y_i^r - N_i^r)$ – before one computes the production staging measures.

that each $D_j^s \geq 1$, with equality if and only if all of the gross output Y_j^s is derived directly from primary factors (with zero purchases of inputs). D_j^s is larger the greater is the use of intermediate inputs as a share of Y_j^s, and particularly so if the directly purchased inputs are themselves multiple stages removed from primary sources of value added.

Fally (2012) and Miller and Temurshoev (2017) establish that D_j^s is the unique solution (up to a normalization) to the recurrence relation: $\mathbf{D}^T = \mathbf{1}^T + \mathbf{D}^T\mathbf{A}$, where $\mathbf{D}$ is the $JS \times 1$ vector that stacks D_j^s as its $((j-1) \times J + s)$-th entry, and $\mathbf{A}$ is the matrix of direct requirements coefficients a_{ij}^{rs}. In other words, country-j, industry-s is one stage more downstream than a weighted-average of country-industries that it purchases inputs from. We thus have: $\mathbf{D}^T = \mathbf{1}^T[\mathbf{I} - \mathbf{A}]^{-1}$, so that D_j^s can also be computed as the $((j-1) \times J + s)$-th column sum of the Leontief inverse, $[\mathbf{I} - \mathbf{A}]^{-1}$. D_j^s is equivalent therefore to the total increase in gross output in the world economy that would be generated by a unit increase in final demand in country-j, industry-s (total backward linkages).[22]

Miller and Temurshoev (2017) and Antràs and Chor (2019) construct these upstreamness and downstreamness measures using the 2013 WIOD release. They document that between 1995 and 2011, GVCs have become longer and more complex, in that the average stage distance of country-industries from primary factors (U_i^r), as well as to final demand (D_j^s), has increased steadily.[23] Interestingly, this "lengthening" of GVCs tapered off after 2008, coinciding with the broader slowdown described earlier in the macro measures of GVC trade. Looking at a leading country case, Chor et al. (2021) combine a measure of industry upstreamness with customs data from China, in order to infer the GVC positioning of Chinese firms. They report a distinct rise in the upstreamness of China's imports up until 2007, even as China's exports became slightly more proximate to final demand, consistent with a widening in the span of stages undertaken within China.[24]

The above measures of production staging lend themselves naturally to studies on the transmission of economic or policy shocks along production chains. Olabisi (2020) finds that industries that are more upstream display greater nominal output and export volatility, a pattern that can be generated by a simple macro model featuring shocks to final demand.[25] Liu (2019) demonstrates that upstream industries also feature a higher "distortion centrality", where the latter concept captures the extent of the welfare gains that would be propagated through an input-output network when efficiency wedges in the industry are reduced. Separately, Kalemli-Özcan et al. (2014) find that firms in more upstream sectors maintain higher levels of working capital; this is consistent with the model of credit provision along production chains, developed by Kim and Shin (2012). Of

[22]The data concerns highlighted in Section 2.2 naturally apply too to these measures of GVC positioning. Insofar as production technologies are not well-described by a single roundabout WIOT matrix, this would introduce measurement error in the upstreamness and downstreamness variables.

[23]By contrast, Fally (2012) finds a decrease in the measure of downstreamness when computed for the benchmark years of the U.S. input-output tables between 1947 and 2002. This suggests that some within-U.S. segments of GVCs were decreasing in stage length over time, even while GVCs as a whole have been spanning more production stages since the mid-1990s.

[24]Li et al. (2015) find that China's state-owned enterprises have maintained particularly high shares of output and value added in upstream industries such as petrochemicals and electricity generation.

[25]This is related to the "bullwhip effect" in supply chain management; see Wang and Disney (2016) for a survey of the operations research literature on this topic.

note for the study of trade policy, Shapiro (2021) uncovers a strong negative relationship between the upstreamness of an industry and the level of protection – both tariffs and non-tariff barriers – enacted in that industry. This constitutes some of the most extensive evidence to date that the pattern of applied protection is in line with the logic of tariff escalation (see Section 6).

Researchers have also applied the measures of production line positioning to explore the empirical relevance of theories on the firm-level structure of GVCs. Using data from Orbis, Rungi and del Prete (2018) uncover a characteristic U-shape relationship between firm-level value added and the upstreamness of their main industry of activity with respect to final demand. This is consistent with the "smile-curve" hypothesis – an observation articulated by former Acer CEO Stan Shih in the early 1990s – that the value added contribution in production chains is highest in the most upstream stages (e.g., R&D) and downstream stages (e.g., marketing and sales).[26] The upstreamness measure has also been used to formally test models of firm organizational decisions along sequential production chains in the presence of contracting and other institutional frictions (see Section 5.3.2; examples include Antràs and Chor, 2013; del Prete and Rungi, 2017; Bolatto et al., 2018; Alfaro et al., 2019). Alfaro et al. (2019) work in particular with a measure that captures the stage distance of an input industry r with respect to the primary industry s of the firm headquarters (rather than measuring this with respect to final demand); this latter variable is of potential interest for researchers seeking a measure of production staging between pairs of industries.[27]

3 Empirical Work: Micro-Level Evidence

We turn next to survey a parallel body of work based on firm-, establishment-, or even transaction-level data, that has uncovered empirical regularities on GVC activity as observed from the ground up. Although not always framed as being about GVCs *per se*, these studies have contributed to a more complete picture of the firm-level correlates of forward participation (exporting) and backward participation (importing) in GVCs (Section 3.1). As richer datasets have become available that track the identities of *both* parties in shipments or transactions, this has further enabled researchers to study buyer-supplier links (Section 3.2) and the relational nature of these interactions (Section 3.3). This micro-empirical work has its pros and cons relative to the macro measurement reviewed in Section 2. The data environments allow more scope for careful investigation of mechanisms and causal identification, by exploiting for example firms' responses to trade liberalization episodes or other policy shocks. However, most existing firm-level studies are limited to a single country due to practical data hurdles, so that one only observes a partial snapshot of GVCs.

[26]This complements work that tests for the "smile curve" in broader cross-sectoral data (Ito and Baldwin, 2021).

[27]This measure is equivalent to the average propagation length – the average number of stages for a shock to be transmitted from one industry to another – formulated in Dietzenbacher et al. (2005). See also Wang et al. (2017) and Imbs and Pauwels (2020) for further extensions.

3.1 Selection into GVC Participation

The advent of large firm-level datasets in research in international trade, starting in earnest in the mid-1990s, has generated a series of stylized facts on firms that export. These speak *inter alia* to the nature of firms' forward participation in GVCs. These features of exporting firms have been documented extensively, in particular in Section 2 of Melitz and Redding (2014a) in Volume 4 of this *Handbook*.[28] Briefly, it is now well-known that only a small share of firms engages in exporting; for example, 18% of U.S. manufacturing firms did so in 1997 (Bernard et al., 2007). Exporting firms are on average larger and more productive than non-exporters, and this advantage often precedes the commencement of a firm's exporting episode. This is consistent with the positive selection of firms into exporting, wherein more productive firms are better able to bear various fixed costs associated with exporting activity.[29] However, existing studies typically do not distinguish between exports of final goods versus intermediates – and so do not strictly identify firms that are GVC participants – nor are there many studies that seek explicitly to tease out the import content of firm-level exports (Kee and Tang, 2016, being a key exception).

In comparison, work on firm-level importing has (until recently) received less spotlight, even though the patterns here are no less robust and no less important for understanding firms' performance. There is an analogous set of stylized facts that points to the relevance of selection into importing, and by extension into backward GVC participation. Firms that import are once again the exception rather than the rule, with only 14% of firms recorded as importers in the U.S. Census of Manufacturing in 1997 (Bernard et al., 2007). The size and productivity advantage of importing firms over non-importers is comparable in magnitude to the corresponding "premia" of exporting firms over non-exporters.[30] Moreover, importing firms that are larger tend to purchase goods from more source countries (Antràs et al., 2017). This points to significant fixed costs associated with each country that firms import from, which firms that lack sufficient scale are unable to afford. The model-based estimates from Antràs et al. (2017) place these fixed costs of importing in the range of US$10,000 to US$56,000 per annum for U.S. firms depending on the source country.[31] Using French data, Blaum et al. (2019) further find that larger firms tend to tilt their import spending shares towards source countries with higher-quality inputs, generating a "non-homothetic" pattern of import demand. This connects with earlier evidence showing that importing firms are able to access more input varieties, and often purchase both domestic and imported inputs that sport higher unit values (e.g., Kugler and Verhoogen, 2009).

For the study of GVCs, firms that both import and export – and hence purvey GVC trade flows

[28] These facts pervade firm-level data in both developed economies (e.g., the U.S., Bernard and Jensen, 1999), as well as in developing countries (e.g. Clerides et al., 1998).

[29] This does not rule out the possibility that the converse relationship – "learning by exporting" – could hold too in practice; see for example de Loecker (2007) for evidence from Slovenian data.

[30] Very similar patterns of importer "premia" have been found across various country settings; see for example Table 8 in Bernard et al. (2007) for the U.S., Table 4 and Table 14 in Muûls and Pisu (2009) for Belgium, Table 7 in Castellani et al. (2010) for Italy, and Appendix Table B1 in Blaum et al. (2018) for France.

[31] Kasahara and Lapham (2013) estimate a similar range of fixed costs of importing – between $28,000 and $117,000 in 1990 US dollars – for Chilean firms in selected manufacturing industries.

– are of particular interest. In light of the above discussion on selection, it comes as no surprise that firms that import and export at the same time are an even smaller share by count of all firms (11% of U.S. manufacturing firms in Bernard et al., 2007). Yet, these GVC participants are crucial for understanding aggregate outcomes due to the large share of economic activity they account for. In the U.S., firms that both import and export constituted close to a third of private-sector employment and an overwhelming share (close to 90%) of U.S. trade in 2000 (Bernard et al., 2009). Similar patterns have been found too in developing countries: Using data from key Chilean manufacturing industries, Kasahara and Lapham (2013) show that the productivity distribution of firms that both import and export is shifted to the right relative to the respective distributions for firms that only import, only export, or do neither.[32]

There are strong conceptual reasons – and an accompanying body of evidence – for viewing the firm-level decisions to import and export as intrinsically linked. A growing number of studies demonstrates that firms that raise their purchases of imported inputs tend to become more productive and to expand the range of products they manufacture. This has been documented for Indonesia (Amiti and Konings, 2007), Chile (Kasahara and Rodrigue, 2008), India (Goldberg et al., 2010), and Hungary (Halpern et al., 2015); the latter two papers point to a substantial role for the extensive margin of import growth, namely access to a greater set of imported input varieties, as a crucial margin behind the improvement in firm performance.[33] On a related note, Bøler et al. (2015) show using Norwegian data that there can be strong complementarities between the decisions to import and to undertake R&D, so that reductions in costs associated with importing can spur R&D-driven productivity improvements (and vice versa). Conversely, Gopinath and Neiman (2014) find that Argentine firms that experienced an adverse shock during the 2001-2002 currency crisis in their access to imported inputs in turn suffered a severe hit to their productivity. It moreover stands to reason that firms that import inputs and become more productive as a result would be better positioned to commence or expand their exporting activities. Evidence establishing this further link to export performance has been reported by Bas (2012) for Argentina, Bas and Strauss-Kahn (2014) for France, and Feng et al. (2016) for China. As noted earlier, many of these firms that both import and export are multinationals, whose sourcing, production and ownership decisions span multiple countries; in this regard, the empirical evidence on horizontal, vertical and export-platform FDI, that was surveyed in Antràs and Yeaple (2014) in Volume 4 of this *Handbook*, is relevant too for shedding light on patterns of GVC activity.

Although the above body of evidence underscores the role of selection into GVC participation, it is useful to take critical stock. By their nature, the underlying firm-level trade data in these studies provides an incomplete snapshot of GVCs, since one does not observe the full set of participants outside the country in question. There are some existing efforts to map out full GVCs, but this is currently limited to a handful of case studies or teardown analyses of specific goods such as the iPod

[32] Lu (2010) is an exception in this regard: Firms that engage in processing trade appear to exhibit a low exporter productivity premium in China.

[33] Colantone and Crinò (2014) document a relationship between imported inputs and an expansion in domestic products for a panel of European countries, albeit using industry-level data.

(Dedrick et al., 2010) or bicycles (World Bank, 2020, Chapter 1). There is scope for more systematic work to unpack GVCs in their entirety, particularly in industries where the set of production inputs can be readily enumerated, as these can deepen our understanding of the forces behind the formation and structure of GVCs.

3.2 Evidence on Buyer-Supplier Matching

Moving beyond data on the import and export activities of individual firms, empirical work on GVCs has benefited from the emergence of datasets that record information on firm-to-firm linkages and even transaction flows. These open a window into examining the characteristics of buyer-supplier matches and the forces that drive their formation.

Within this line of work, the studies that speak most directly to GVCs are those which utilize datasets containing importer-exporter trade transactions. An early example on this front is Blum et al. (2010), who undertook a laborious merge of customs data from Chile and Argentina.[34] Researchers have since tapped data from customs authorities that either maintain foreign firm identifiers or that contain variables that allow foreign firms to be tracked sufficiently closely; such data have been explored from Norway (Bernard et al., 2018), Colombia (Eaton et al., 2016; Bernard et al., 2019), Costa Rica, Ecuador and Uruguay (Carballo et al., 2018), France (Kramarz et al., 2020), and the U.S. (Monarch and Schmidt-Eisenlohr, 2017; Heise et al., 2019).[35] Two additional forms of data on buyer-supplier matches have provided complementary insights. First, a number of datasets report on links, but have no or partial information on values transacted. Databases of publicly-listed firms such as Compustat often include disclosures of major customers or suppliers (which Atalay et al., 2011, use to map out production networks). Several data providers now extend coverage of such supply chain information beyond publicly-listed firms, including Capital IQ (used in Lim, 2018) and Factset Revere (used in Huang et al., 2020; Amiti et al., 2020; Charoenwong et al., 2021).[36] Second, researchers have unlocked access to administrative value added tax (VAT) records, that provide a close to full profile of buyer-supplier matches within the formal domestic economy. Such VAT data have been studied for Belgium (Bernard et al., 2019; Dhyne et al., 2020), Chile (Huneeus, 2018), Costa Rica (Alfaro-Ureña et al., 2020), Turkey (Demir et al., 2021), and Ecuador (Adão et al., 2020), among others, and have yielded particularly rich insights when merged with other administrative data such as firm-level customs records.

These studies have unearthed a set of empirical regularities. We overview these below, but would also direct readers to Bernard and Moxnes (2018) for a comprehensive account of these facts on buyer-supplier matches. In the typical firm-to-firm dataset, the distributions of the number of

[34] See also Blum et al. (2009) who worked to merge customs records from Chile and Colombia.

[35] In U.S. import transactions, information on the identity of the foreign supplier is contained in the "manufacturer ID" variable on U.S. customs forms. See Monarch and Kamal (2018) for work that assesses and improves on the reliability of this identifier.

[36] These commercial datasets rely on proprietary methods for aggregating supply chain information from company reports, filings, and announcements. While coverage is not universal, this may be sufficient for applications where it is the largest firms that are most consequential. For example, the three papers cited which use Factset Revere study the impact on firms of the U.S.-China tariff war as propagated through their supply chain links.

buyers per seller (or importers per exporter) and the number of sellers per buyer (or exporters per importer) are very skewed. Only a small subset of sellers successfully matches and trades with a large number of buyers – and similarly, only a small fraction of buyers are linked with a large number of sellers – even though these links account for the bulk of transacted value. Moreover, one often detects a pattern of "negative degree assortativity": Sellers that have few links (and are thus presumably smaller and less productive firms) tend on average to sell to buyers that have many connections (and are thus presumably larger and more productive). Conversely, for sellers who have many connections, the marginal – and hence also the average – buyer that they sell to exhibits a smaller number of links.

Taken together, these empirical regularities are consistent with selection not just in importing or exporting *per se*, but in the formation of buyer-supplier matches in domestic and global value chains. Such selection could be driven for instance by the presence of match-specific fixed costs (as in Bernard et al., 2018), so that it is more productive sellers that can amortize these costs to form matches with a larger number of buyers.[37] Several studies have indeed uncovered patterns of adjustment in buyer-supplier matches following trade policy or transport shocks that point to the presence of such fixed costs in link formation. Using the Tokyo Shoko credit agency database, Bernard et al. (2019) demonstrates how the extension of a high-speed passenger rail-line increased the number of buyer-supplier links between firms in southern Japan and the rest of the country. This is highly suggestive of the importance of face-to-face meetings for reducing costs associated with search or information acquisition about potential suppliers.[38] Benguria (2021) finds that the advent of the U.S.-Colombia Free Trade Agreement prompted U.S. exporters to switch their firm-to-firm matches to establish links with larger Colombian importers. This is consistent with the higher profits from exporting encouraging U.S. firms to incur search costs to seek a better match in the local market. Examining the response of Mexican textile and apparel exporters to the removal of the Multi-Fiber Agreement quotas, Sugita et al. (2020) shows that selection into exporting to the U.S. became more stringent, in the face of the more intense competition from Chinese exports in the U.S. market; at the same time, surviving Mexican exporters ended up being paired on average with lower capability U.S. buyers.

We round off this subsection by briefly reviewing work that has exploited buyer-supplier link data to good effect to investigate spillovers or shock propagation through value chains. Alfaro-Ureña et al. (2020) use data from Costa Rica to trace out how domestic firms benefit when they become suppliers to multinational firms. On a less benign note, Barrot and Sauvagnat (2016) show that natural disasters that impact suppliers in turn hurt the market values of their major customers (as identified in Compustat), particularly if the inputs provided are highly specific. Boehm et al. (2019) study how the 2011 Tohoku earthquake disrupted the supply chains of Japanese multinationals,

[37] Demir et al. (2021) document a further feature in buyer-supplier matching present in VAT data from Turkey: Skill-intensive firms tend to purchase inputs from skill-intensive suppliers, which the authors relate to the former's use of higher-quality inputs in their production processes.

[38] Miyauchi (2019) uses the same Japanese dataset to discipline a model of network formation that features agglomeration effects in buyer-supplier matching.

as evidenced through the impact on the production of their affiliates in the U.S. Carvalho et al. (2020) examine the aggregate implications of this earthquake, focusing on the transmission of shocks through Japan's domestic firm-to-firm network.[39] Kashiwagi et al. (2021) document how companies that were not directly hit by Hurricane Sandy were nevertheless adversely affected if they had links with firms located in severely afflicted areas.

3.3 Evidence on the Relational Nature of GVC Links

The growing body of evidence on firm-to-firm links raises a natural question: What distinguishes buyer-supplier links within GVCs from regular market-based spot transactions? Toward this end, a stream of work has spotlighted the *relational* nature of buyer-supplier links within GVCs, as underscored by how GVC links often exhibit durability over time, rather than being one-shot interactions (World Bank, 2020).

Social scientists outside of economics have actually long recognized this relational nature of GVCs. The extensive literature by sociologists and economic geographers on "governance" forms has traditionally drawn a distinction between "buyer-driven" and "producer-driven" value chains, so termed to reflect the party in the relationship that exercises more decision-making and coordinating power (Gereffi, 1994, 1999). This typology was augmented by Gereffi et al. (2005), who introduced the notion of "relational value chains". These latter arrangements are characterized by production processes that require high levels of input customization or relationship-specific investment; the link between a buyer and its supplier is thus "built-up over time", with repeated interactions often accompanied by exchanges of tacit knowledge. This generates a "mutual dependence" that makes "the costs of switching to new partners high" (Gereffi et al., 2005, p.86).[40]

The above description of "relational value chains" dovetails with evidence on the average duration of buyer-supplier links in GVCs. Using the U.S. Census Longitudinal Foreign Trade and Transaction Database (LFTTD), and focusing on arm's-length imports by non-wholesale and non-retail entities, Monarch and Schmidt-Eisenlohr (2017) find that new buyer-supplier links (defined at the detailed HS 10-digit level) made up more than half of all new import relationships by count, but only for about a quarter of U.S. imports by value in 2011. Put otherwise, while there is dynamism in the formation of new links, it is continuing relationships that account for a much greater share of trade value. Consistent with this, the value of transactions rises over time with the number of consecutive years that a buyer-supplier pair remains active, while the link hazard rate falls steadily with relationship age.[41] Martin et al. (2020) report similar patterns using a rich French customs dataset on firm-to-firm trade with the E.U. at the monthly frequency. Based on this, they propose

[39]See Todo et al. (2015) who find that Japanese firms in the earthquake area were better able to recover if they had supply chain links with domestic firms that were not directly affected.

[40]For completeness, the five value chain governance modes in Gereffi et al. (2005) are: hierarchical (or "producer-driven"), market (or "buyer-driven"), relational, modular, and captive.

[41]Eaton et al. (2014) uncover a similar pattern when zooming in on U.S. imports from Colombia. These expand upon the findings of Besedeš and Prusa (2006a, 2011), who document an analogous set of stylized facts using detailed product-level trade flows, though without exploiting confidential firm identifiers. Besedeš and Prusa (2006b) show that the survival probability of a given product-by-country import flow into the U.S. is higher for differentiated products.

a measure of "relationship-stickiness" at the HS 6-digit level, that is constructed off the average duration of buyer-supplier links after controlling for transaction size. Their "relationship-stickiness" measure correlates positively with other product-level characteristics that one might associate with relational GVC links, including specificity (Rauch, 1999), contract-intensity (Nunn, 2007), and complexity (Hausmann and Hidalgo, 2014). Examining U.S. imports from China in the LFTTD, Monarch (2020) finds that the survival rate for a given buyer-supplier link is systematically higher for products that are more skill-intensive or contract-intensive. Of note, U.S. buyers who switch a supplier are disproportionately more likely to select a new seller from the same Chinese city, consistent with the costs of searching and gathering information being lower in a geographic location that is already familiar to the U.S. firm.

The above empirical work delivers useful benchmark facts on the persistence of importer-exporter links. It however remains several steps removed from decomposing the economic forces that could explain the cross-product variation observed in relationship duration. GVCs that involve a lot of customized inputs may see more persistent buyer-supplier matches, as repeated interactions can help sustain investments in relationship-specific effort when the parties involved are sufficiently patient (Baker et al., 2002).[42] GVC links could also be sticky because it is costly to search for alternative suppliers, or because there are barriers to the diffusion of information (Allen, 2014; Startz, 2016). At the same time, the persistence of links may itself depend on the size of the pool of potential buyers or suppliers, so that considerations related to market power could be relevant too. Understanding the relative importance of these various explanations for the relational nature of GVC links is an interesting avenue for future work.

On this last note, a recent vein of micro-empirical studies at the intersection of international trade and development economics has contributed valuable insights into the forces that affect the formation and durability of supply chains links. This has been achieved through the collection of original, fine-grained information on participants and transactions in specific supply chain settings, that often involve local suppliers and foreign buyers. One message that has emerged from this work is that repeated interactions can be an important means for establishing a seller's reputation. In the context of the Kenyan rose export market, Macchiavello and Morjaria (2015) find that the value of cut flowers sold by a supplier to its foreign buyer tends to increase as the relationship ages, consistent with the seller developing a good reputation over time with the buyer. Related to this, Startz (2016) shows how international travel to meet face-to-face with foreign suppliers plays an important role for Nigerian traders, when it is difficult for the suppliers to credibly establish reputation from a distance. Such studies have also provided evidence on forces that can threaten the durability of a match, including: higher global market prices that raise the seller's outside option (Macchiavello and Morjaria, 2015; Macchiavello and Miquel-Florensa, 2018), and the presence of more competing local buyers (Macchiavello and Morjaria, 2020).

Relational contracting arrangements also serve to maintain incentives for the parties in a supply

[42] Kukharskyy (2016) draws on a measure of cultural affinity towards "long-term orientation" from the social psychology literature (specifically, Hofstede et al., 2010), to test whether the implications of the Baker et al. (2002) framework are consistent with patterns in U.S. intrafirm trade flows.

chain link, particularly in developing-country contexts where formal legal institutions are weak. In the Bangladesh garment supply market, Cajal-Grossi et al. (2020) find that relational buyers pay higher markups than spot buyers for products that are observationally equivalent on many dimensions. The higher markups paid by relational buyers can be interpreted as akin to an "efficiency wage", to incentivize suppliers to meet benchmarks for the reliable delivery of orders at short notice when such contingencies arise. The relational nature of supply chain links also shapes payment and trade financing terms (Antràs and Foley, 2015); for example, Brugués (2020) demonstrates how sellers in Ecuador's manufacturing supply chains use the implicit promise to maintain a link to incentivize buyers to make good on the trade credit extended to them.

4 Modeling GVCs: Macro Approaches

Having discussed empirical work in the last two sections, we next turn to overview theoretical work on the modeling of GVCs, beginning with "macro" approaches. As explained in the Introduction, we use this label to refer to work where the unit of analysis is the country-industry and where the emphasis is largely quantitative in nature. All the frameworks discussed below share the common feature of emphasizing the role of trade in intermediate inputs and of global intersectoral linkages in shaping the response of the world economy to various types of shocks, most notably trade policy shocks. Beyond providing a useful quantitative tool, these frameworks also provide a structural interpretation of the cells in a WIOT, and in some cases, these frameworks offer a microfoundation for the types of assumptions researchers implicitly make when invoking input-output analysis tools to compute the value added content of trade flows or the positioning of countries in GVCs (as described in Section 2). Although the vast majority of the papers reviewed in this section were written in the last ten years, we should of course acknowledge that quantitative work in international trade has a long tradition as a branch of the field of computable general equilibrium (or CGE) modeling (see Kehoe, 2005; Hertel, 2013; Hillberry and Hummels, 2013).

4.1 Roundabout Models: The Caliendo-Parro Model

We begin by reviewing the "roundabout" model in Caliendo and Parro (2015), which has quickly become a benchmark model in the field. Caliendo and Parro (2015) present a multi-industry extension of the Eaton and Kortum (2002) Ricardian model of international trade. We describe the basics of the model, how it connects with the "macro" measurement literature of GVCs reviewed above, and how this facilitates the computation of policy counterfactuals.

4.1.1 Theoretical Framework

Environment and Notation. Consider a world with $J \geq 1$ countries and $S \geq 1$ sectors or industries. Producers in all sectors produce an output that can be interchangeably used as an intermediate input or as a final (consumer) good. There is a unique primitive factor of production, equipped labor, which is inelastically supplied in each country. All production technologies feature constant returns to scale and all producers behave competitively. As in Section 2, we use *subscripts* i and j (and occasionally k) to refer to countries, and *superscripts* r and s to refer to industries, with origin countries or industries on the left, and destination countries or industries on the right.

Preferences and Technology. The representative consumer in each country has preferences over the output of the S sectors given by:

$$u(C_j) = \prod_{s=1}^{S} \left(C_j^s\right)^{\alpha_j^s}, \tag{6}$$

where C_j^s denotes consumption of a sector-s aggregate, C_j denotes the vector of the C_j^s's consumed in country j, α_j^s is the share of industry s in the expenditure of the country-j representative consumer, and $\sum_{s=1}^{S} \alpha_j^s = 1$.

Within each industry s, there is a continuum of varieties indexed by $\omega^s \in [0,1]$. Production of each variety is a Cobb-Douglas function of equipped labor, as well as intermediate inputs. More specifically, in country i, the production function for each industry-s variety is given by:

$$y_i^s(\omega^s) = z_i^s(\omega^s) \left(l_i^s(\omega^s)\right)^{1-\sum_{r=1}^{S} \gamma_i^{rs}} \prod_{r=1}^{S} \left(\mathcal{M}_i^{rs}(\omega^s)\right)^{\gamma_i^{rs}}. \tag{7}$$

Note that $\mathcal{M}_i^{rs}(\omega^s)$ is the amount of composite intermediates from industry r used in the production of variety ω^s in country i. The exponent γ_i^{rs} is the (constant) share of production costs spent on intermediate inputs from sector r by each industry-s producer in country i. It is assumed that $0 < \gamma_i^{rs} < 1$, and moreover that $0 < \sum_{r=1}^{S} \gamma_i^{rs} < 1$, so that the equipped labor share (or simply, value added share) of production costs is strictly positive in all sectors and countries. The productivity shifter $z_i^s(\omega^s)$ is an i.i.d. draw from a Fréchet distribution with cumulative density function $F_i^s(z) = \exp\{-T_i^s z^{-\theta^s}\}$. The scale parameter T_i^s governs the state of technology of country i in industry s, while $\theta^s > 1$ governs (inversely) the dispersion of productivity in industry s across producers worldwide, thereby shaping comparative advantage.

The country-i composite in industry s, which is used both for final consumption (C_i^s), as well as to provide inputs to other sectors r ($\mathcal{M}_i^{sr}$), is a CES aggregate with elasticity $\sigma^s > 1$ over the set of varieties on the unit interval:

$$Q_i^s = \left(\int q_i^s(\omega^s)^{(\sigma^s-1)/\sigma^s} d\omega^s\right)^{\sigma^s/(\sigma^s-1)}, \tag{8}$$

where $q_i^s(\omega^s)$ denotes the quantity of variety ω^s that is ultimately purchased, naturally from the lowest-cost source country. It is worth reiterating that the same CES aggregator over varieties applies to the industry-s composite, whether it is being consumed in final demand or being used as an intermediate input; we will return to this issue below.

Note that the framework captures the notion that countries not only import consumer goods, but also intermediate inputs from various industries and countries, with these imported inputs embodying *foreign value added*. Similarly, countries not only export consumer goods, but also intermediate inputs, thus generating *domestic value added* in production and exports of foreign countries. In sum, the Caliendo and Parro (2015) model captures important aspects of GVCs.

Equilibrium. 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. We ignore tariffs and their implied tariff revenue, but they are modeled in Caliendo and Parro (2015). The solution to this discrete choice problem yields an expression for the share of expenditure X_j^s of country j on industry-s varieties (intermediate or final goods) that come from country i:

$$\pi_{ij}^s = \frac{T_i^s (c_i^s \tau_{ij}^s)^{-\theta^s}}{\sum_{k=1}^J T_k^s (c_k^s \tau_{kj}^s)^{-\theta^s}}. \tag{9}$$

Country j's spending on country-i, industry-s's output is higher the more advanced 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:

$$c_j^s = \Upsilon_j^s w_j^{1-\sum_{r=1}^S \gamma_j^{rs}} \prod_{r=1}^S \left(P_j^r\right)^{\gamma_j^{rs}}, \tag{10}$$

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, which is straightforward to derive following Eaton and Kortum (2002). The last two sets of equilibrium conditions are associated with goods-market clearing for each industry in each country, and with trade balance (which can easily accommodate an exogenous national deficit D_j). We provide the full set of equilibrium conditions in Online Appendix A.1.

4.1.2 Mapping the Model to Data

How does the Caliendo and Parro (2015) model map to available data from World Input-Output Tables (or WIOTs)? Remember from Figure 1 in Section 2 that a WIOT contains information on intermediate purchases by industry s in country j from sector r in country i, which we denote by Z_{ij}^{rs}. It also contains information on the final-use expenditure in each country j on goods/services originating from sector r in country i, which we denote by F_{ij}^r. Finally, the values of country-industry gross output Y_j^s and value added V_j^s, as well as country-specific trade deficits D_j, can all be computed from the WIOT. The model thus offers transparent theoretical counterparts to all cells in a WIOT. Furthermore, notice that the functional forms imposed by the model – namely Cobb-Douglas technologies, CES aggregators over varieties, and Fréchet distributions of productivity – imply that in line with the implicit assumption made in Section 2, the direct requirements $a_{ij}^{rs} = Z_{ij}^{rs}/Y_j^s$ are constant and given by (see equation (9)):

$$a_{ij}^{rs} = \frac{\sum_{k=1}^{J} Z_{kj}^{rs}}{Y_j^s} \frac{Z_{ij}^{rs}}{\sum_{k=1}^{J} Z_{kj}^{rs}} = \frac{\gamma_j^{rs}}{\sum_{t=1}^{S} \gamma_j^{ts}} \frac{T_i^s (c_i^s \tau_{ij}^s)^{-\theta^s}}{\sum_{k=1}^{J} T_k^s (c_k^s \tau_{kj}^s)^{-\theta^s}}.$$

In other words, the model not only provides a structural interpretation of all the entries of a WIOT, but it also offers a microfoundation that rationalizes the type of matrix manipulations underlying the use of input-output analysis to compute the value added content of trade flows (for more on this, see Aichele and Heiland, 2018).

It is worth stressing, however, a significant limitation of the Caliendo and Parro (2015) model in matching data from a WIOT. In particular, because production technologies and trade costs are common for inputs and final goods, and because preferences only vary across countries on account of sectoral spending shares, this framework imposes a unique market share of a given country i in the purchases of output of a given sector r by a destination country j, regardless of whether that output is designated for final-use or for use as an intermediate by other industries, or:

$$\frac{F_{ij}^r}{\sum_{k=1}^{J} F_{kj}^r} = \frac{Z_{ij}^{rs}}{\sum_{k=1}^{J} Z_{kj}^{rs}},$$

across all sectors s. To provide a concrete example, the model imposes that when buying finished products from the automobile industry (e.g., assembled cars), U.S. consumers spend their income across foreign sources of these finished goods in the same proportion in which U.S. auto makers buy parts and components across foreign suppliers. As explained in Section 2.2, although traditional proportionality assumptions used to construct WIOTs tend to generate very similar if not identical trade shares for final goods and for intermediate inputs, more recent and sophisticated WIOTs have attempted (and will continue to attempt) to break these proportionality assumptions when constructing the tables.

A simple way to sidestep this issue, which Caliendo and Parro (2015) follow, is to simply aggregate intermediate inputs and final-good purchases, and to map the trade share π_{ij}^s in the model to an empirical trade share computed as simply $X_{ij}^s / \sum_{i'} X_{i'j}^s$, where X_{ij}^s is country j's spending on industry-s varieties (intermediate or final goods) originating in i. As we shall discuss next, conditional on the structure of the model being the correct one (and thus ignoring the existing deviations of the model from actual WIOTs), it turns out that one can perform counterfactual analyses with minimal estimation requirements.

4.1.3 Counterfactual Analysis: The Hat-Algebra Approach

As Caliendo and Parro (2015) note, the hat-algebra approach to counterfactual analyses devised by Dekle et al. (2008) in a one-sector model works equally well in their multi-sector model. More specifically, suppose one is interested in computing the counterfactual value of some key equilibrium variables of the model (such as real income per capita) following a shock to some of the parameters. Caliendo and Parro (2015) demonstrate that this can be achieved with only 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 (see Online Appendix A.1 for details).

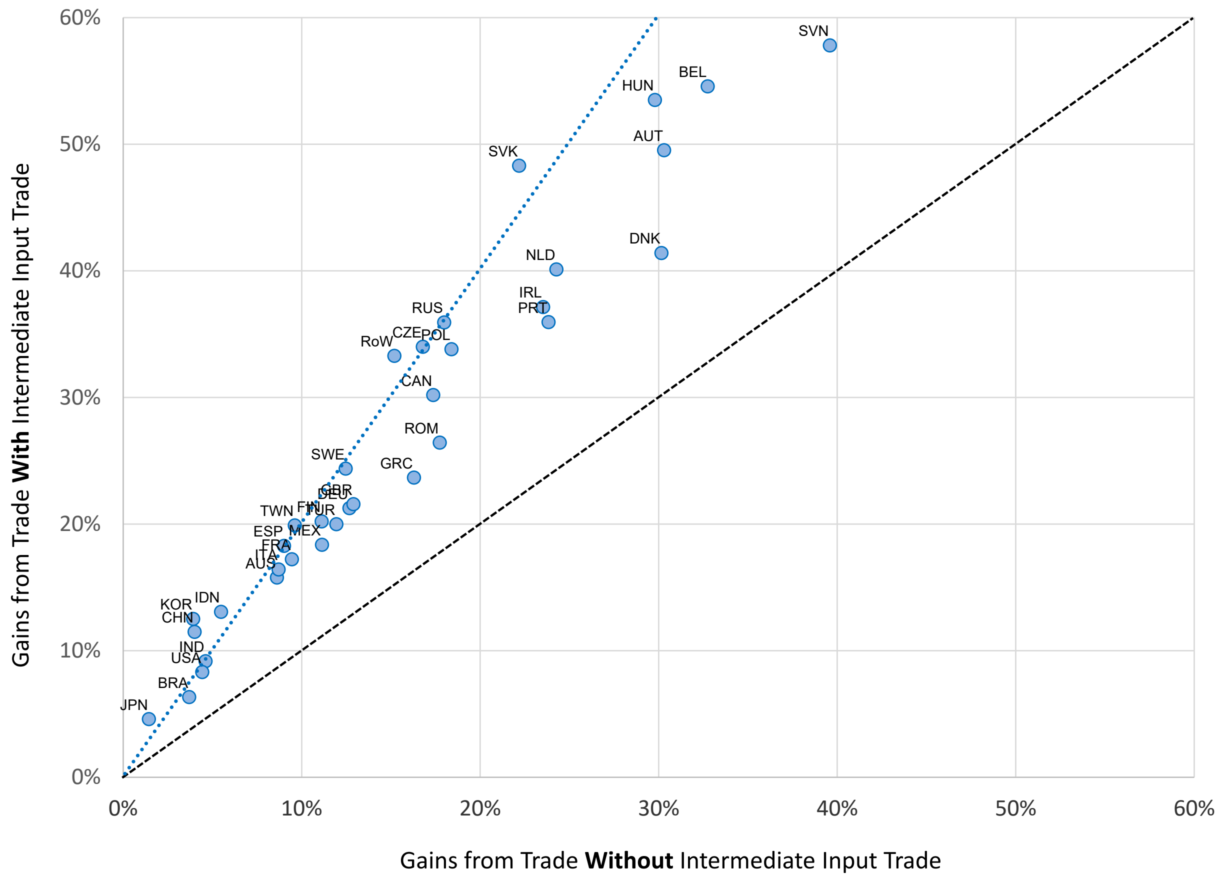
To estimate these key trade elasticities, Caliendo and Parro (2015) back out a log-linear estimating equation that amounts to running a triple-differences normalization of trade shares on a triple-differences normalization of asymmetric trade barriers such as tariffs. This results in trade elasticities ranging from 0.37 for "Other Transport" to 51.08 for "Petroleum". With these at hand and the other calibrated parameters, they quantify the consequences of NAFTA's tariff reductions. They find that although the model predicts that these tariff reductions increased intra-bloc trade very substantially (by 118% for Mexico, 11% for Canada, and 41% for the U.S.), the real income implications of NAFTA are much more muted. In particular, according to the model, these tariff reductions increased real income in Mexico and the United States (by 1.31% and 0.08%, respectively) but decreased real income in Canada (by 0.06%).

Despite these meager effects, it is important to emphasize that the gains from trade cost reductions in multi-sector models with intersectoral input linkages tend to be much larger than those implied in one-sector trade models, and are also larger than in multi-sector models without traded inputs (see Table 11 in Caliendo and Parro, 2015). This is further illustrated in Costinot and Rodríguez-Clare (2014), who compute the "gains from trade" (or real income losses from moving to autarky) for various countries and for various possible environments. It turns out that these gains from trade are captured by the neat formula:

$$GT_j = 1 - \prod_{s=1}^{S} \prod_{r=1}^{S} \left(\pi_{jj}^s\right)^{\widetilde{\gamma}_j^{rs} \alpha_j^s / \theta^s},$$

where remember that π_{jj}^s is the own trade share in sector j, α_j^s is the share of industry s in country j's final consumption, and θ^s is the sectoral trade elasticity. The new term $\widetilde{\gamma}_j^{rs}$ is the r-by-s-th element of the Leontief inverse matrix $[\mathbf{I} - \mathbf{\Gamma}_j]^{-1}$, where $\mathbf{I}$ is the $S \times S$ identity matrix, and $\mathbf{\Gamma}_j$ is an $S \times S$ matrix with typical element γ_j^{rs}. To illustrate the role of GVC linkages, it is particularly interesting to compare the estimates in columns 2 and 4 of their Table 4.1, which correspond to the gains from trade in a multi-sector competitive model with no input trade versus a multi-sector competitive model with input trade (as in Caliendo and Parro, 2015). These values are plotted in Figure 4. As is clear from the figure, gains from trade are higher for all countries in a world with intermediate input linkages, and the differences are quite large for some countries (the blue dotted line corresponds to a doubling of the gains from trade). On average, the gains from trade are 75% larger in a world of intermediate input trade. Giri et al. (2021) provide a more extensive analysis of the effects of several sources of sectoral heterogeneity for the size of the aggregate income gains from trade.

Figure 4: Gains from Trade With and Without Input Trade



4.1.4 Applications and Extensions

The last ten years have seen an explosion of quantitative work in international trade, and the awareness that intermediate input flows are a first-order feature has led many researchers to adopt the Caliendo and Parro (2015) framework as the basis for conducting several types of counterfactual exercises. We review several "off-the-shelf" applications of their model in Online Appendix A.1. Beyond these, we highlight and discuss several more substantive extensions below.

First, several sets of authors have worked to relax some of the assumptions of the framework so as to allow the model to fit more of the cells in a WIOT. An early attempt is Alexander (2017), who develops a two-sector extension of Caliendo and Parro (2015) that delivers distinct trade shares for intermediate inputs and for final goods by allowing the technology parameter T_i^r to differ depending on whether producers in sector r produce final goods for consumers or inputs for other industries. More recently, Antràs and Chor (2019) have relaxed the assumption that iceberg trade costs are independent of the use of the goods being traded, and they show that this simple extension allows the model to fully match *all* entries of a WIOT.

A second salient line of extensions has sought to relax the strong functional forms built into the Caliendo and Parro (2015) model. For instance, Caliendo et al. (2017) relax the Cobb-Douglas assumptions on preferences in (6) and on technology in (7), and show that this delivers an endogenous matrix of input-output (or direct requirement) links. Baqaee and Farhi (2019) go even further and study nonparametric scenarios, while demonstrating that the gains from international integration can be significantly larger when input substitutabilities are lower than the unit ones imposed in Cobb-Douglas economies (see also Fally and Sayre, 2018).

A third set of contributions has introduced features from the economic geography literature, such as multiple regions across countries, and partial labor mobility across regions within countries. Two salient examples are Caliendo et al. (2018), who explore the implications of productivity shocks for the U.S. economy in the presence of interindustry and interregional intermediate input linkages, and Caliendo et al. (2019), who conduct a general-equilibrium analysis of the China trade shock, thus connecting with the reduced-form work of Autor et al. (2013) exploiting geographical variation across U.S. commuting zones in the incidence of import competition from China.

We close this subsection by briefly mentioning a few additional extensions, which have permitted the quantitative evaluation of counterfactuals that were not feasible in the original Caliendo and Parro (2015) model. Levchenko and Zhang (2016) present a dynamic model that allows them to trace the implications for trade flows and for real income of growth in sectoral total factor productivity in 72 countries and 19 sectors over 50 years. Di Giovanni et al. (2014) apply the same framework to isolate the implications of trade integration with China for other countries in the world economy. Caselli et al. (2020) incorporate sector-specific productivity shocks into the framework and study the extent to which international specialization increases or decreases the exposure of countries to productivity shocks abroad. Morrow and Trefler (2017) explore another interesting extension which allows for multiple factors of production, to structurally study the implications of changes in trade costs, endowments and technology for the factor content of trade. More recently, Bagwell et al. (2018) have embedded Caliendo and Parro (2015) into a model of international tariff negotiations, to study the counterfactual implications of tariff negotiations in the absence of the most-favored-nation clause. Rodríguez-Clare et al. (2020) have incorporated nominal rigidities into the framework to study the effects of trade shocks (and the China shock, in particular) on unemployment.

4.1.5 Critical Assessment

As the previous subsection has illustrated, the Caliendo and Parro (2015) model has quickly become a staple in the toolkit of international trade economists. It is important to close this section, however, with a critical assessment of the framework and its usage.

First, although the hat-algebra approach to counterfactual analysis is a remarkably useful tool, the minimal estimation requirements imposed by it are not innocuous. To be more precise, practitioners of this approach often praise how parsimonious it is relative to CGE models, which involve the estimation of thousands of parameters. An often glossed-over fact, however, is that the hat-algebra approach requires the model to fit the data *exactly*, which amounts to calibrating all parameters of the model (or combinations of them) to values that ensure this exact fit. In particular, this requires one to calibrate trade costs to infinity for the numerous country-sector to country-sector trade flows that take a value of zero in the data. Whether one should describe this approach as being "parsimonious" is thus not entirely clear-cut.

Second, and more substantially, although quantitative work often requires strong assumptions on functional forms, calibrating thousands of parameters to fit the data exactly can be problematic for the validity or reliability of the counterfactual predictions of those models. The problem is similar to overfitting in regression analysis leading to poor out-of-sample performance. As recently shown in Dingel and Tintelnot (2020), this is a particularly severe problem in spatial environments in which the data the model is fitted to contains a significant number of zeros. Note that even in the WIOD – a WIOT focusing on relatively rich countries – the share of zeroes is 13.7% in the matrix of input-use coefficients and 46.8% in the matrix of final-use column vectors.[43] It is then perhaps not too surprising that, as discussed in Kehoe et al. (2017), the performance of the Caliendo and Parro (2015) model in predicting the actual bilateral trade implications of NAFTA – as measured by the change in trade flows from 1991 to 2006 – is rather underwhelming. A natural counterargument is that "many things" happened between 1991 and 2006, but the lack of "external" evidence supporting the out-of-sample performance of these models remains problematic, and a clear area with room for improvement in future research.

4.2 Multi-Stage Approaches

The framework in Caliendo and Parro (2015) features intermediate input trade and intersectoral linkages, and thus captures the fact that global production takes places in "a series of stages with each stage adding value," to paraphrase our definition of GVCs in the Introduction. But by adopting a roundabout structure, the model essentially assumes that goods are produced via an endless sequence of steps, with each stage using inputs from prior stages in an infinite loop. Furthermore, all producers in a given sector use the same bundle of inputs in production, and operate the same technology in equation (7) regardless of the stage of production.

In this section, we will turn attention to "macro" approaches that specify multi-stage production technologies featuring a discrete number of stages that add value in a pre-determined order. To simplify matters, we will focus on outlining a model with just two stages and no use of inputs or materials other than those coming from the initial stage. In Online Appendix A.2, we develop extensions of the model with more than two stages, also incorporating the use of a composite bundle of inputs at each stage, as in roundabout models.

4.2.1 A Simple Multi-Stage Model

Let us consider a simple multi-country Ricardian model of trade with two-stage production inspired by the pioneering work of Yi (2003), and related to the frameworks in Yi (2010), Johnson and Moxnes (2019), and Antràs and de Gortari (2020). The world economy consists of $J \geq 1$ countries

[43] Based on the WIOD (2013 release), for the year 2011.

in which consumers derive utility from differentiated varieties in a single sector. Preferences across varieties are CES, as in equation (8) in the roundabout model reviewed in Section 4.1.

On the technology side, the good is produced combining two stages that need to be performed sequentially. Production in the initial stage $n = 1$ only uses labor, while the second stage of production combines labor with the good produced in the first stage. More specifically, we write these production technologies as follows:

$$y_i^1(\omega) = z_i^1(\omega^s) l_i^1(\omega^s), \tag{11}$$

and:

$$y_i^2(\omega^s) = \left(z_i^2(\omega) l_i^2(\omega)\right)^{\alpha_2} \left(y_i^1(\omega)\right)^{1-\alpha_2}, \tag{12}$$

where $\alpha_2 \in (0,1)$ denotes the labor share in stage-2 production, and $z_i^n(\omega)$ is labor productivity at stage n in country i. Firms are perfectly competitive and the optimal location $\ell(n) \in \{1, \ldots, J\}$ of the different stages $n \in \{1, 2\}$ of the value chain is dictated by cost minimization.

Countries differ in three key aspects: (i) their size, as reflected by the measure L_i of "equipped" labor available for production in each country i (labor is inelastically supplied and commands a wage w_i); (ii) their geography, as captured by a $J \times J$ matrix of iceberg trade costs $\tau_{ij} \geq 1$; and (iii) their technological efficiency, as determined by the labor productivity terms $z_i^n(\omega)$. Following the lead of Eaton and Kortum (2002), we initially assume that $z_i^n(\omega)$ is drawn independently (across goods and stages) from a Fréchet distribution with cumulative distribution function $F_i^n(z) = \exp\{-T_i^n z^{-\theta}\}$.

Consider the lead-firm problem of choosing the least-cost path of production to deliver consumption good ω to consumers in country j. Given equations (11) and (12), this amounts to choosing locations $\ell^j(1)$ and $\ell^j(2)$ to minimize:

$$c\left(\ell^j(1), \ell^j(2)\right) = \tau_{\ell^j(2)j} \left(\frac{w_{\ell^j(2)}}{z_i^2(\omega)}\right)^{\alpha_2} \left(\frac{\tau_{\ell^j(1)\ell^j(2)} w_{\ell^j(1)}}{z_i^1(\omega)}\right)^{1-\alpha_2}. \tag{13}$$

Following the logic of Eaton and Kortum (2002), the hope is that the Fréchet assumption on the labor productivities $z_i^1(\omega)$ and $z_i^2(\omega)$ will deliver a convenient distribution for the equilibrium marginal cost of production of active GVCs, which will then facilitate a description of the general equilibrium of the model. Unfortunately, the minimum cost (13) associated with a given GVC path is *not* characterized by a particularly tractable distribution. The reason is that, although the minimum of a series of Fréchet draws is itself distributed Fréchet, and both $z_i^1(\omega)^{1-\alpha_2}$ and $z_i^2(\omega)^{\alpha_2}$ are Fréchet distributed, the product of Fréchet random variables is *not* Fréchet distributed. As a result, papers adopting this lead firm approach to cost minimization with stage-specific Fréchet productivity draws need to resort to numerical methods to approximate the solution of their models, even when restricting the analysis to two-stage chains (see Yi, 2010; Johnson and Moxnes, 2019).

Antràs and de Gortari (2020) instead develop two alternative approaches that permit a sharp and exact characterization of the equilibrium, much as in the work of Eaton and Kortum (2002) and Caliendo and Parro (2015). The first approach considers a decentralized equilibrium in which stage-specific producers (or consumers) minimize costs only at their individual stage, and they do so with incomplete information about the productivity of certain suppliers upstream from them.

The second approach to gain tractability consists in simply treating the *overall* (i.e., chain-level) unit cost of production of a GVC flowing through a sequence of countries as a draw from a Fréchet random variable. To motivate this assumption, consider a given production path $\boldsymbol{\ell} = \{\ell(1), \ell(2)\} \in \mathcal{J}^2$, where $\mathcal{J}$ is the set of countries in the world. Its associated *chain-level* production cost is naturally a function of trade costs, composite factor costs and the state of technology of the various countries involved in the chain. Yet, two chains flowing across the same countries in the exact same order may not achieve the same overall productivity due to (unmodeled) idiosyncratic factors, such as compatibility problems, production delays, or simple mistakes.

More formally, and building on the cost function in (13), Antràs and de Gortari (2020) assume that the overall productivity of a given chain $\boldsymbol{\ell} = \{\ell(1), \ell(2)\}$ is distributed Fréchet with a shape parameter given by θ, and a location parameter that is a function of the states of technology in all countries in the chain, as captured by $\left(T^1_{\ell(1)}\right)^{1-\alpha_2}\left(T^2_{\ell(2)}\right)^{\alpha_2}$. A direct implication of this assumption is that the unit cost associated with serving consumers in a given country j via a given chain $\boldsymbol{\ell}$ is also distributed Fréchet, which then allows one to readily invoke some key results from Eaton and Kortum (2002) to characterize the relative prevalence of different GVCs.

Specifically, it is straightforward to verify that the share of country j's income spent on final goods produced under a particular GVC path $\boldsymbol{\ell} \in \mathcal{J}^2$ is given by:

$$\pi_{\boldsymbol{\ell}j} = \frac{\left(\left(T^1_{\ell(1)}\right)^{\alpha_1}\left(\left(w_{\ell(1)}\right)^{\alpha_1}\tau_{\ell(1)\ell(2)}\right)^{-\theta}\right)^{1-\alpha_2} \times \left(T^2_{\ell(2)}\right)^{\alpha_2}\left(\left(w_{\ell(2)}\right)^{\alpha_2}\tau_{\ell(2)j}\right)^{-\theta}}{\sum_{\boldsymbol{\ell}\in\mathcal{J}^2}\left(\left(T^1_{\ell(1)}\right)^{\alpha_1}\left(\left(w_{\ell(1)}\right)^{\alpha_1}\tau_{\ell(1)\ell(2)}\right)^{-\theta}\right)^{1-\alpha_2} \times \left(T^2_{\ell(2)}\right)^{\alpha_2}\left(\left(w_{\ell(2)}\right)^{\alpha_2}\tau_{\ell(2)j}\right)^{-\theta}}, \tag{14}$$

and in addition, the exact ideal price index P_j in country j is a simple power function of the denominator in (14), with exponent $-1/\theta$.

A few observations regarding equation (14) are in order. First, this equation collapses to that in the Eaton and Kortum (2002) framework when $N = 1$ (and thus $\alpha_2 = 1$). Second, and quite intuitively, GVCs that involve countries with higher states of technology T_i or lower labor costs w_i will tend to feature disproportionately in production paths leading to consumption in j. Third, high trade costs penalize the participation of countries in GVCs, but their effect "compounds" along the chain: if all trade costs in a particular GVC increase by 10%, this GVC's spending share decreases by $\theta(2-\alpha_2)$ percent, rather than by θ in the roundabout model (see Yi, 2010, for more on this magnification effect). Another implication of this compounding is that, in choosing their optimal path of production, firms will be more concerned about reducing trade costs in relatively downstream stages than in relatively upstream stages, as reflected in the higher exponent for $\tau_{\ell(2)j}$ than for $\tau_{\ell(1)\ell(2)}$ in equation (14). As Antràs and de Gortari (2020) demonstrate, this feature of the model generates a centrality-downstreamness nexus by which, *ceteris paribus*, relatively more central countries will tend to have comparative advantage and specialize in relatively downstream stages, a nexus for which they provide suggestive evidence.

Let us briefly comment on how the results above extend to an environment with $N > 2$ stages of production. We relegate the details to Online Appendix A.2, but the key is that, 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) demonstrate that the share of country j's spending on final goods produced under a particular GVC path $\boldsymbol{\ell} = \{\ell(1), \ell(2), ..., \ell(N)\} \in \mathcal{J}^N$ is given by an expression – see equation (A.11) in Online Appendix A.2 – that is a straightforward generalization of that in equation (14). In that Online Appendix, we also outline how to derive the remaining equilibrium conditions of the N-stage model, including the set of labor-market clearing conditions pinning down wages worldwide.

4.2.2 Gains from Trade

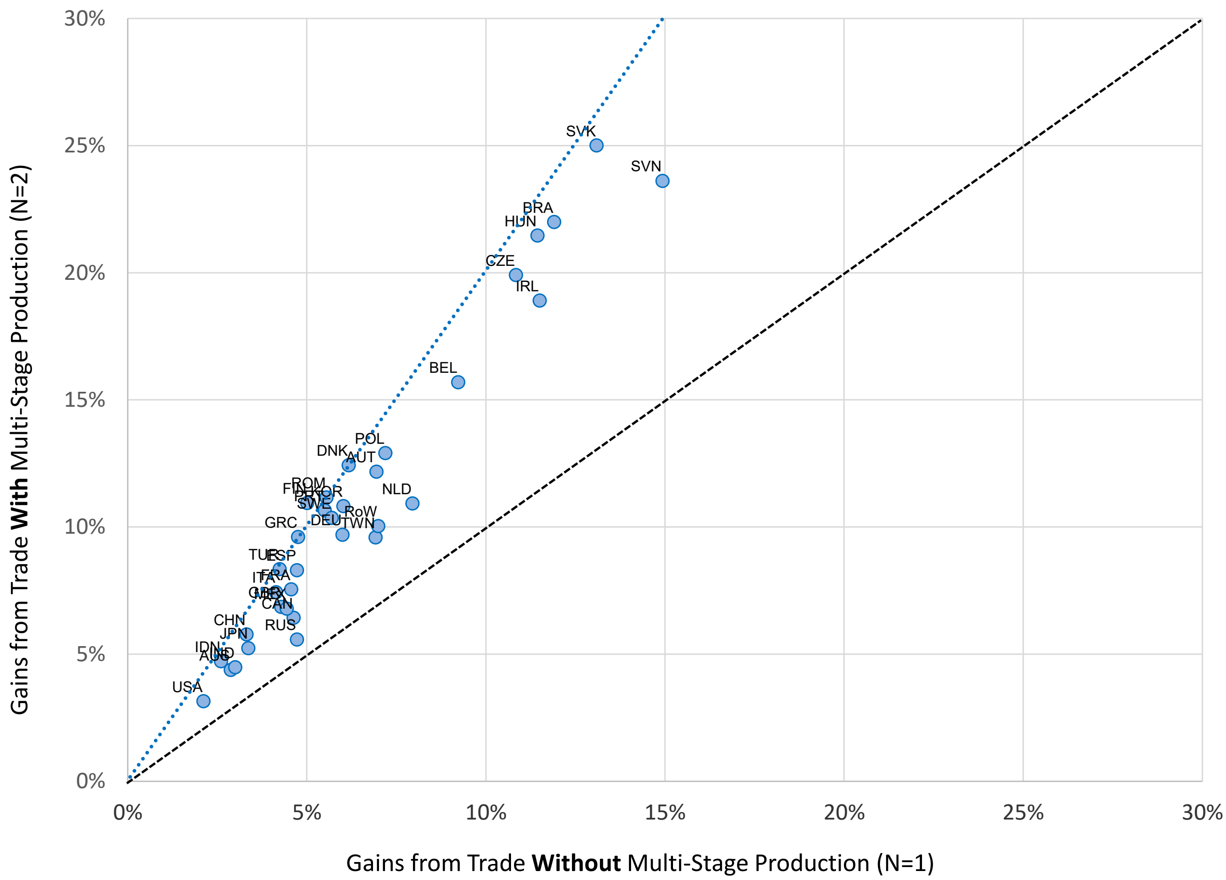
To study the real income implications of trade in this framework, it is useful to first consider a "purely-domestic" value chain that performs all N stages in a given country j to serve consumers in the same country j. Let us denote this domestic chain by $\boldsymbol{j} = (j, j, ..., j)$. Antràs and de Gortari (2020) show that real income is given by:

$$\frac{w_j}{P_j} = \left(\kappa\left(\tau_{jj}\right)^{\sum_{n=1}^{N}\beta_n}\right)^{-1}\left(\frac{\prod_{n=1}^{N}\left(T_j^n\right)^{\alpha_n\beta_n}}{\pi_{\boldsymbol{j}j}}\right)^{1/\theta}, \tag{15}$$

where κ is a constant that depends only on θ and σ. This formula is analogous to the one that applies in the Eaton and Kortum (2002) framework and the wider class of models studied by Arkolakis et al. (2012). An important difference, however, is that $\pi_{\boldsymbol{j}j}$ is *not* the aggregate share of spending on domestic intermediate or final goods (which is readily available in input-output datasets), but rather the share of spending on goods that are produced *entirely* through domestic supply chains, an object which cannot be directly measured. As a result, the sufficient statistic approach advocated by Arkolakis et al. (2012) is not feasible in this setting, and one needs to estimate the model structurally to back out $\pi_{\boldsymbol{j}j}$ from available data. For a similar reason, the hat algebra approach to counterfactual analysis proposed by Dekle et al. (2008) and implemented by Caliendo and Parro (2015) is not feasible in a multi-stage setting.

We can however draw some qualitative implications of the model for the aggregate income consequences of trade shocks. Notice that the share of spending $\pi_{\boldsymbol{j}j}$ on purely domestic chains will, other things equal, be lower, the larger is the number of stages, and thus the gains from trade emanating from multi-stage models are expected to be larger on this account. This result is similar to the one derived by Melitz and Redding (2014b) in an Armington framework with sequential production, and also bears some resemblance to Ossa (2015)'s argument that the gains from trade can be significantly larger in multi-sector models, with stages here playing the role of sectors in Ossa's framework. In their estimated model, Antràs and de Gortari (2020) find that the gains from trade (i.e., the income losses from reverting to autarky) obtained in their model are much larger when $N = 2$ than those obtained from a version of their model without multiple stages (i.e., $N = 1$). These values are plotted in Figure 5 for the same set of countries considered by Costinot and Rodríguez-Clare (2014) and previously plotted in Figure 4. As is evident from the figure, multi-stage production increases the gains from trade in all countries in a world with intermediate input linkages, and the differences are quite large for most countries (the blue dotted line corresponds to a doubling of the gains from trade). On average, the gains from trade are 72% larger in a world with multi-stage production.

Figure 5: Gains from Trade With and Without Multi-Stage Production



4.2.3 Mapping to Data, Extensions and Applications

Our discussion so far has centered on a stylized model of multi-stage production, in which production processes are purely sequential. In Online Appendix A.2, we briefly demonstrate the flexibility and applicability of this type of framework, and we show how it can easily nest both the Eaton and Kortum (2002) and Caliendo and Parro (2015) models. In the process, we also show how to map closed-form expressions from these multi-stage models to the observable data points contained in a WIOT. 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.

It is worth briefly mentioning some additional recent applications of quantifiable multi-stage models of GVCs. Beyond the work of Yi (2003, 2010), and Johnson and Moxnes (2019) mentioned above, another noteworthy contribution is Fally and Hillberry (2018). The main distinguishing feature of their framework is that they model production processes with a continuum of stages, and they consider the determination of the optimal set of stages that are carried out within firms and within countries. Other authors have recently applied or extended the framework in Antràs and de Gortari (2020) in interesting directions. Zhou (2020) uses a variant of the model to study the quantitative implications of the U.S.-China trade war, leveraging the fact that multi-stage frameworks allow for an independent analysis of the consequences of levying tariffs on inputs and on final goods. Lee and Yi (2018) develop a multi-factor extension to study the interplay between the rise of GVCs and increased wage inequality, while Sposi et al. (2021) embed it in a neoclassical growth model with capital accumulation. Finally, Yang (2018) incorporates within-country geography into the model to study the role of infrastructure in shaping the participation of countries in GVCs.

4.2.4 Critical Assessment

A feature of multi-stage models of GVCs that has hindered their widespread use is the fact that they are much harder to apply than roundabout models. Even when the use of functional form assumptions dramatically simplifies the characterization of the equilibrium of the model, the fact that the hat-algebra approach cannot be used in this setting implies that the demands on estimation are much larger for this line of models. For instance, although a multi-sector model with multi-stage production can easily be written and solved, such a model is much harder to estimate because it requires estimating hundreds of technological parameters that can no longer be easily extracted from WIOTs. Having said this, and as we have argued in Section 4.1.5, the claim that roundabout models only require estimating a handful of parameters is somewhat disingenuous, as the hat-algebra approach essentially boils down to calibrating thousands of parameters to fit the data exactly, which may lead to overfitting biases. We envision a future in which work to develop macro models of GVCs will result in a more fruitful combination of calibration and estimation techniques.

5 Modeling GVCs: Micro Approaches

As we argued in Section 3, world trade flows are dominated by a small number of large firms that actively participate in GVCs and that capture large market shares in their sector's exports and imports. In more plain words, it is not countries or "country-industries" that participate in GVCs, but rather individual firms in those country-industries that choose to do so. In this section, we will review a body of work that has shed light on the decisions firms face over whether to participate in GVCs, and when designing their optimal GVC strategies.

We will proceed as follows. Initially, in Section 5.1, we focus on decentralized frameworks in which firms make decisions only pertaining to the specific stages of GVCs in which they produce. In particular, we draw a distinction between firm-level models of forward GVC participation, and firm-level models of backward GVC participation, in line with the discussion of the empirical literature in Section 3.1. Next, in Section 5.2, we turn to an overview of theoretical frameworks that consider the problem of a lead firm who chooses optimally the location of production of *all* the stages in a value chain. Finally, we close in Section 5.3 with an overview of work highlighting the "relational nature" of GVCs.

5.1 GVC Participation: Decentralized Approaches

5.1.1 Selection into Forward GVC Participation

Consider a world consisting of J countries where consumers have preferences over a continuum of differentiated products. As in the models in Section 4, preferences are CES and given by:

$$Q_j^F = \left(\int_{\omega \in \Omega_j^F} q_j^F(\omega)^{(\sigma-1)/\sigma} \, d\omega \right)^{\sigma/(\sigma-1)} \tag{16}$$

in country j, where $\sigma > 1$ is the elasticity of substitution across varieties, and Ω_j^F is the set of consumption varieties available in country j. The resulting demand for variety ω in country j is $q_j^F(\omega) = E_j P_j^{\sigma-1} p_j^F(\omega)^{-\sigma}$, where E_j is total spending in country j, $p_j^F(\omega)$ is the price of variety ω, and P_j is the ideal price index associated with (16).

Consider next the supply side of the model. The only factor of production is "equipped labor", which individuals in each country i supply inelastically in an amount L_i. Each final-good variety ω is produced by a single firm: the market structure in this final-good sector is characterized by monopolistic competition, and there is free entry into the industry. Production of final-good varieties employs equipped labor to assemble a bundle of intermediates, much as in the "macro" models reviewed in Section 4. The main novel feature here is that technologies feature increasing returns to scale. More specifically, in order to produce, firms need to incur a fixed overhead cost equal to f_i^F units of labor. Unit costs in final-good production are in turn given by:

$$c_i^F(\omega) = \frac{1}{z_i^F(\omega)} w_i^{\gamma} \left(P_i^I \right)^{1-\gamma}, \tag{17}$$

where P_i^I is the price index associated with the bundle of intermediates used in production, and is analogous to expression (10) in the Caliendo and Parro (2015) framework in Section 4. We assume that the bundle of inputs is a CES aggregator of a continuum of inputs, or:

$$P_i^I = \left(\int_{\varpi \in \tilde{\Omega}_i} p_i^I(\varpi)^{(\rho-1)/\rho} d\varpi \right)^{\rho/(\rho-1)}, \tag{18}$$

where $\tilde{\Omega}_i$ is the set of input varieties available in country i, $p_i^I(\varpi)$ is the price paid in country i for input ϖ, and ρ governs the degree of substitutability across inputs. To simplify matters we will focus on the case in which all final-good producers share the same productivity $z_i^F(\omega) = z_i^F$ and in which trade costs on final goods across countries are purely ad valorem in nature and denoted by τ_{ij}^F when shipping from i to j.

Intermediate inputs are produced using only equipped labor under a technology given by:

$$f_i^I + q_i^I(\varpi) = z_i^I(\varpi) l_i^I(\varpi), \tag{19}$$

where f_i^I is an overhead cost incurred by suppliers and $z_i^I(\varpi)$ is labor productivity in input production. This upstream sector is also monopolistically competitive and there is free entry into the sector. Firms face an additional fixed cost of entry f_i^e incurred before their productivity level $z_i^I(\varpi)$ is drawn from some distribution $G\left(z^I\right)$. Intermediate inputs are tradable across countries and incur iceberg trade costs τ_{ij}^I, but in addition, firms exporting inputs need to incur a fixed cost f_{ij}^X in order to export them from country i to market j. This last fixed cost will generate selection into exporting and thus into forward GVC participation.

It is informative to first consider the case in which final goods are prohibitively costly to trade across countries ($\tau_{ij}^F \to \infty$). In such a case, we show in Online Appendix B.1, that the total demand for intermediate inputs by final-good producers in country j is given by:

$$\frac{\sigma - 1}{\sigma} (1 - \gamma) w_j L_j, \tag{20}$$

and is thus a simple multiple of aggregate income in market j. The profits obtained by an intermediate producer in i when exporting in country j are in turn given by:

$$\pi_{ij}^I\left(z_i^I\right) = \left(z_i^I\right)^{\sigma-1} \left(\tau_{ij}^I w_i\right)^{1-\sigma} B_j^I - w_i f_{ij}^X, \tag{21}$$

where $B_j^I = \frac{\sigma-1}{\sigma} (1-\gamma) \frac{1}{\rho} \left(\frac{\rho}{\rho-1}\right)^{1-\sigma} w_j L_j \left(P_j^I\right)^{\rho-1}$. It is then clear that the behavior of intermediate input producers will be identical to that in the Melitz (2003) framework. In particular, only those firms from i with productivity $z_i^I \geq \tilde{z}_i^I$ will find it optimal to export inputs to country j, and these firms will engage in forward GVC participation. This is in line with the empirical fact that exporters (regardless of whether they are final-good or intermediate-input producers) tend to be more productive than non-exporters (see Section 3.1). This selection into exporting will operate independently across countries, that is, the decision to export to a given destination j is not affected by this same firm's decisions in other markets. This feature greatly simplifies the construction of the general equilibrium of the model, particularly when one assumes that the distribution $G\left(z^I\right)$ from which intermediate input producers draw their productivity is Pareto in all countries (see Chaney, 2008; Helpman et al., 2008).

In sum, when final goods are nontradable, a model of forward GVC participation essentially reduces to a Melitz-style framework of selection into exporting. Note, however, that when final goods are nontradable, the value added embodied in the exported intermediate inputs does not cross two borders, so it is not entirely clear that one should consider this a model of GVC participation.

With that in mind, in Appendix B.1 we consider an extension with bounded trade costs for final goods. This extension produces similar predictions but the analysis is significantly more intricate.

5.1.2 Selection into Backward GVC Participation

We next turn to outlining a model of backward GVC participation which builds on the work of Antràs et al. (2017).[44]

Environment and Assumptions. The framework again features a final-good (or downstream) sector and an intermediate-input (or upstream) sector. Consumer preferences over manufacturing goods are identical to those in the model in the last subsection: individuals value the consumption of differentiated varieties according to Q_j^F in (16).[45]

Technology and market structure in the final-good sector are also largely analogous to that previous model. There exists a measure N_j^F of final-good producers in each country $j \in \mathcal{J}$, each producing a distinct differentiated variety ω, the industry is characterized by monopolistic competition, and there is free entry into the industry. Furthermore, production combines labor and intermediate inputs exactly as in the cost function in (17), and firms need to incur an overhead cost of production of f_i^F units of country i's labor before any production can occur. Unlike in the previous model, we will now focus attention to the case in which labor efficiency z_i^F in downstream production is heterogeneous across producers and drawn from a continuous cumulative distribution $G_i\left(z_i^F\right)$. As in Melitz (2003), final-good producers only learn their productivity z_i^F after paying a fixed cost of entry, but they are assumed to choose their sourcing strategy with knowledge of that core productivity level. The main novel assumption in this framework is that a firm from country i only acquires the capability to import intermediates inputs from a source country j after incurring a fixed cost equal to f_{ij}^M units of labor in country i (at a cost $w_i f_{ij}^M$). We denote by $\mathcal{J}_i\left(z_i^F\right) \subseteq \mathcal{J}$ the set of countries for which a firm based in i with productivity z_i^F has paid the associated fixed cost of offshoring, and often refer to $\mathcal{J}_i\left(z_i^F\right)$ as the *sourcing strategy* of a firm.

To emphasize the implications of selecting into importing, and thus of backward GVC participation, we follow Antràs et al. (2017) in assuming that the intermediate-input sector is perfectly competitive with labor productivity differences across inputs and countries specified as in Eaton and Kortum (2002). More specifically, we adopt the technology in equation (19), but we set overhead costs $f_i^I = 0$ and assume that the value of z_i^I for a given location i is drawn (independently across locations and inputs) from a Fréchet distribution, $F_i(z) = \exp\{-T_i z^{-\theta}\}$. Beyond the fixed cost importers need to incur to purchase inputs from a given country, shipping intermediate inputs across countries also involves iceberg trade cost τ_{ij}^I.

[44] We will refrain from reviewing the vast literature on offshoring and global sourcing (see Antràs and Yeaple, 2014, for an overview).

[45] A significant difference is that tackling the general equilibrium of this type of models is computationally difficult, so Antràs et al. (2017) assume that the manufacturing sector faces a perfectly elastic supply of labor.

Equilibrium with Nontradable Final Goods. As in our discussion of the model of forward GVC participation, it again proves useful to first solve the model for the case in which final goods are prohibitively costly to trade across borders. As shown by Antràs et al. (2017), the Eaton-Kortum structure of the intermediate-input sector implies that conditional on a given global sourcing strategy $\mathcal{J}_i\left(z_i^F\right)$, the share of input purchases sourced from any country j by a firm from i with productivity z_i^F is given by:

$$\chi_{ij}\left(z_i^F\right) = \frac{T_j\left(\tau_{ij}^I w_j\right)^{-\theta}}{\sum_{k\in\mathcal{J}_i\left(z_i^F\right)} T_k\left(\tau_{kj}^I w_k\right)^{-\theta}}, \tag{22}$$

if $j \in \mathcal{J}_i\left(z_i^F\right)$, and by $\chi_{ij}\left(z_i^F\right) = 0$ if $j \notin \mathcal{J}_i\left(z_i^F\right)$. The numerator $T_j\left(\tau_{ij}w_j\right)^{-\theta}$ in equation (22) captures the *sourcing potential* of country j from the point of view of firms in i, while the denominator in this expression, which equals the sum of sourcing potentials of the countries included in a firm's sourcing strategy, summarizes the *sourcing capability* of that firm. The price index for intermediate inputs faced by a firm with productivity z_i^F is a simple power function (with exponent $-1/\theta$) of this sourcing capability. Intuitively, adding a new location to the set $\mathcal{J}_i\left(z_i^F\right)$ increases competition across supplying sources and leads to a lower price index paid by the firm for the bundle of inputs. Invoking constant-markup pricing, one can then express the firm's profits conditional on a sourcing strategy $\mathcal{J}_i\left(z_i^F\right)$ as:

$$\pi_i^F\left(z_i^F\right) = \left(z_i^F\right)^{\sigma-1}\left(w_i\right)^{-(\sigma-1)\gamma}\left(\kappa\sum_{k\in\mathcal{J}_i\left(z_i^F\right)} T_k\left(\tau_{ik}^I w_k\right)^{-\theta}\right)^{(\sigma-1)(1-\gamma)/\theta} B_i - w_i\sum_{k\in\mathcal{J}_i\left(z_i^F\right)} f_{ik}^M, \tag{23}$$

where B_i is a residual demand term that depends on aggregate spending on manufacturing goods, and the final-good price index in that sector.

As is clear from equation (23), when deciding whether to add a new country j to the set $\mathcal{J}_i\left(z_i^F\right)$, the firm trades off the reduction in costs associated with the inclusion of that country in the set $\mathcal{J}_i\left(z_i^F\right)$ – which increases the sourcing capability – against the payment of the additional fixed cost $w_i f_{ij}^M$. This tradeoff is similar to the one faced by exporters in our model of forward GVC participation (see equation (21)), who also trade off higher operating profits (via increased export revenue) versus higher fixed costs. Nevertheless, there is a very important difference between selecting into exporting and selecting into importing. In the former case, and given the standard assumption of constant marginal costs of production, the decision to service a given market is independent of that same decision in other markets. Conversely, in models of selection into importing, firms select into offshoring precisely to affect their marginal cost. As a result, the marginal change in profits in equation (23) from adding a country to the firm's set $\mathcal{J}_i\left(z_i^F\right)$ depends on the set of other countries from which a firm imports, as well as those countries' characteristics. The problem of a firm optimally choosing its sourcing strategy is thus much harder to characterize, both analytically as well as quantitatively, since it requires solving a combinatorial problem with 2^J elements (where

J is the number of countries). Despite these complications, Antràs et al. (2017) derive a series of theoretical results that facilitate a fruitful study of a multi-country model of backward GVC participation.

First, Antràs et al. (2017) note that given the fact that the profit function in (23) is log-supermodular in core productivity z_i^F and the firm's sourcing capability, no matter what the actual optimal set $\mathcal{J}_i\left(z_i^F\right)$ may be, more productive firms necessarily choose global sourcing strategies that give them (weakly) higher sourcing capabilities; this implies that their cost advantage is magnified by their sourcing decisions, thus generating an increased skewness in the size distribution of firms. Second, given the structure of the model, whether the decisions to source from different countries are complements or substitutes ends up depending only on the relative size of $(\sigma-1)(1-\gamma)$ and θ. Selection into importing features complementarity across markets whenever $(\sigma-1)(1-\gamma)>\theta$, that is, when: (i) demand is relatively elastic (so profits are particularly responsive to variable cost reductions); (ii) inputs are relatively important in production (low γ); and (iii) input efficiency levels are relatively heterogeneous across markets (so that the reduction in expected costs achieved by adding an extra country in the set of active locations is relatively high). Third, whenever sourcing decisions are complementary, one can use standard tools from the monotone comparative statics literature to show that the sourcing strategies of firms follow a strict hierarchical structure in which the number of countries in a firm's sourcing strategy is (weakly) increasing in the firm's core productivity level, in line with empirical evidence. Fourth, in this same "complements case", one can also show that, holding constant the market demand level B_i, a reduction in any trade friction (τ_{ij}^I or f_{ij}^M) leads to a (weak) increase in the set $\mathcal{J}_i\left(z_i^F\right)$ and also increases (weakly) firm-level bilateral input purchases from *all* countries. More specifically, the model predicts that a decrease in sourcing costs from China – perhaps due to a "China shock" applying to imported inputs – is expected to lead to an increase in firm-level U.S. intermediate input demand not only from China, but also from other sources including the U.S. itself, as long as one controls for demand conditions, a prediction for which Antràs et al. (2017) present reduced-form evidence.

Beyond these comparative static results, Antràs et al. (2017) show that whenever global sourcing decisions are complements, one can adopt an iterative algorithm first proposed by Jia (2008), which uses lattice theory to greatly reduce the dimensionality of the firm's optimal sourcing strategy problem, a feature which in turn allows them to estimate and simulate the model with limited computing power. In subsequent work, Arkolakis and Eckert (2017) have shown that a variant of the same type of algorithm can be implemented to solve for the extensive margin of sourcing even when sourcing decisions are substitutes rather than complements, and Yang (2020) provides an application to an oligopolistic setting.

We have seen so far that a model of selection into backward GVC participation produces much richer predictions than a baseline model of forward GVC participation. Strictly speaking, however, the fact that the framework above focuses on a model with nontradable final goods implies that goods never cross two borders, so again it is not obvious that it captures GVC participation. Fortunately, extending the model to the case of tradable final goods is straightforward, and we present the details of such an analysis in Online Appendix B.2. The main new insight that emerges from this extension is that, in the plausible complements case $(\sigma - 1)(1 - \gamma)/\theta > 1$, the model delivers a complementarity between the exporting and importing margins of firms, in line with the findings of the empirical literature.

Related Work and Extensions. Although we have largely focused on the work by Antràs et al. (2017), the literature on importing and backward GVC participation is quite extensive. The body of empirical papers demonstrating the productivity effects of global sourcing was reviewed in Section 3.1. On the theoretical front, the work of Blaum et al. (2018) and Blaum et al. (2019) is also noteworthy. Blaum et al. (2018) build on the insights of Arkolakis et al. (2012) to provide sufficient statistics to measure the aggregate effects of input trade on consumer prices in an environment in which different firms may feature heterogeneous levels of involvement in global sourcing. In Blaum et al. (2019), the same set of authors incorporate vertical differentiation in inputs into a model of global sourcing.

We close this section by referring the reader to Online Appendix B.2, where we outline a series of extensions of the framework of backward GVC participation in Antràs et al. (2017). (Some of these extensions will be discussed in more detail in Sections 5.1.3 and 5.3).

5.1.3 Two-Sided Matching Frameworks

The micro approaches developed so far consider environments in which firms make operational decisions that lead them to select into export destinations or input sources. We next overview a body of work that instead considers frameworks in which firms match with other firms rather than with "countries"; this builds naturally off the evidence on patterns of buyer-supplier matching described in Section 3.2.

Models with Deterministic Matching. Bernard et al. (2018) consider a framework that shares many features with the model of forward GVC participation developed in Section 5.1.1. As in that model, there is a final-good sector where a continuum of producers with heterogeneous productivity levels assembles consumer goods under increasing returns to scale and monopolistic competition, and there is an intermediate-input sector that produces inputs with labor, also with increasing returns and under a monopolistically competitive market structure. Intermediate inputs are tradable but shipping them across borders entails both iceberg trade costs as well as fixed costs, which are paid by the exporter. The main innovation of Bernard et al. (2018)'s framework is that they interpret these exporting fixed costs as relationship-specific in nature, and thus incurred whenever attempting to reach out to a new costumer, even when a firm is already servicing other costumers in the same destination market. More specifically, the profits an intermediate input producer from i with productivity z_i^I obtains when selling inputs to a final-good producer in country j with productivity

z_j^F is given by:

$$\pi_{ij}^I\left(z_i^I, z_j^F\right) = \left(\frac{\tau_{ij}^I w_i / z_i^I}{P_j^I\left(z_j^F\right)}\right)^{1-\sigma} P_j^I\left(z_j^F\right)\mathcal{M}_j\left(z_j^F\right) - w_j f_j^X,$$

where P_j^I denotes the price index for inputs – and $\mathcal{M}_j\left(z_j^F\right)$ the corresponding input demand – associated with a final-good producer. These objects in turn depend on the extensive margin decisions of all intermediate input producers, which significantly complicate the analysis of the equilibrium. Nevertheless, because more productive final-good firms will tend to be larger and demand more inputs, a larger set of suppliers will optimally select into selling to them, and this will in turn reduce the price index faced by final-good producers and further boost their input demand. Bernard et al. (2018) solve for firm behavior and also for the industry equilibrium of the model whenever labor productivities upstream and downstream follow Pareto distributions.

Among other results, Bernard et al. (2018) show that their framework predicts that both the distributions of buyers per exporter and of exporters per buyer are characterized by many firms with few connections and a few firms with many connections. Intuitively, large and productive suppliers will select into selling not just to large and productive final-good producers, but also to smaller and less productive buyers. Similarly, large and productive buyers will have many exporters (even less efficient ones) willing to sell to them. As already mentioned in Section 3.2, Bernard et al. (2018) show that this assortative matching pattern is consistent with evidence from Norwegian transaction-level customs data from 2004–2012. They further show that the "buyer margin" of international trade explains a large fraction of the variation in aggregate trade. Finally, they aggregate the model at the industry level, and show that it retains many of the properties of models of firm heterogeneity with CES preferences and a Pareto distribution of productivity, such as the Chaney (2008) model.[46]

In Online Appendix B.3, we 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). 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. As we show in Online Appendix B.3, in the "complements case", the model predicts that more efficient firms will feature 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. Furthermore, more efficient suppliers will be "selected" by a larger share of final-good producers. 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.

Although both frameworks outlined above feature firm-to-firm matching and trade, relationships are initiated by investments from only one party in the transaction. We are not aware of more "symmetric" models of the type outlined above – with product differentiation, monopolistic

[46] Related work considering the "buyer margin" of trade includes Arkolakis (2010) and Carballo et al. (2018).

competition and firm heterogeneity– in which both upstream and downstream (or both sellers and buyers) incur fixed costs to *deterministically* initiate relationships, although some models of search and matching often have that feature.

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 (cf., Jackson, 2010) to develop stochastic models of how firm-to-firm production networks are formed. Due to space constraints, we relegate an overview of this literature to Online Appendix B.4.

Overall, the body of work reviewed in this section is attempting to shift the focus from models in which firms make decisions about participating in GVCs in isolation, to environments in which firms' decisions and the shocks they face interact with each other, thus shaping the dynamics of economic activity and of aggregate trade flows in ways that are much richer than in environments without firm-to-firm links. The benefit of this approach is that it should result in more reliable quantitative and structural work, but this comes at the cost of a much greater complexity in analyzing and estimating these models.

5.2 Designing GVCs: The Lead-Firm Problem

Having outlined a number of decentralized approaches, we now turn attention to lead-firm approaches to the design of GVCs. The material in this section is motivated by the facts described in Section 3 indicating that world trade flows are crucially shaped by the operational decisions of a relatively small number of large firms. These "superstar" firms not only make exporting and importing decisions, but more generally, they design strategies to deliver their branded products to foreign consumers at the lowest possible cost. This leads them to seek suitable suppliers for the various stages in their value chains, and it also leads them to set up assembly plants in various countries to minimize the cost at which they make their goods available to distant consumers. In this section, we will outline a few variants of this lead-firm problem.

5.2.1 Multi-Stage Production

We begin by developing a simple model of firm behavior that formalizes the problem faced by a lead firm choosing the location of the various production stages involved in manufacturing a consumer good. The good is produced combining N stages that need to be performed sequentially, and there are J countries in which consumers derive utility from consuming the good and in which the various stages can be produced. The last stage of production can be interpreted as final assembly and is indexed by N. As in previous sections, we will often denote the set of countries $\{1, ..., J\}$ by $\mathcal{J}$ and the set of production stages $\{1, ..., N\}$ by $\mathcal{N}$. At each stage $n > 1$, production combines a local composite factor with the good finished up to the previous stage $n - 1$. Production in the initial stage $n = 1$ only uses the local composite factor.

Although the main insights of this section extend to more general specifications of technology, we will follow Antràs and de Gortari (2020) and focus throughout on Cobb-Douglas technologies at each stage. More precisely, we denote the unit cost of production of stage n in country $\ell(n)$ as:

$$p^{n}_{\ell(n)}(\boldsymbol{\ell}) = \frac{1}{z_{\ell(n)}} \left(a^{n}_{\ell(n)} c^{n}_{\ell(n)}\right)^{\alpha_n} \left(p^{n-1}_{\ell(n-1)}(\boldsymbol{\ell})\, \tau_{\ell(n-1)\ell(n)}\right)^{1-\alpha_n}, \text{ for all } n \in \mathcal{N}, \tag{24}$$

where $\boldsymbol{\ell} = \{\ell(1), \ell(2), ..., \ell(N)\}$ is the path of production, $z_{\ell(n)}$ is a country-specific total factor productivity (TFP) term that is common for all stages, $a^{n}_{\ell(n)}$ is the unit composite-factor requirement that is specific to stage n in country $\ell(n)$, $c^{n}_{\ell(n)}$ is the cost of the composite factor used at stage n in country $\ell(n)$, $\alpha_n \in (0,1)$ denotes the cost share of the composite factor at stage n, and $\tau_{\ell(n-1)\ell(n)}$ are iceberg trade costs associated with shipping goods from $\ell(n-1)$ to $\ell(n)$. Because the initial stage of production uses solely the local composite factor, we set $\alpha_1 = 1$.

Note that equation (24) also applies to the final assembly stage N, and a good completed in $\ell(N)$ after following the path $\boldsymbol{\ell}$ is available in any country j at a cost $p^{F}_{j}(\boldsymbol{\ell}) = p^{N}_{\ell(N)}(\boldsymbol{\ell})\, \tau_{\ell(N)j}$ (where we use the superscript F to denote finished goods). For each country $j \in \mathcal{J}$, the goal of the firm is then to choose the optimal path of production $\boldsymbol{\ell}^{j} = \left\{\ell^{j}(1), \ell^{j}(2), ..., \ell^{j}(N)\right\} \in \mathcal{J}^{N}$ that minimizes the cost $p^{F}_{j}(\boldsymbol{\ell})$ of providing the good to consumers in that country j. The remainder of this section will seek to characterize the solution to this problem. The questions we will attempt to answer are: what forces shape the optimal assignment of stages to countries, and how do they exactly do so?

Free Trade: Comparative Advantage. To begin, consider a simple variant of equation (24) in which we set all trade costs to 0, so $\tau_{ij} = 1$ for all $i, j \in \mathcal{J}$, and in which $z_{\ell(n)} = 1$, so productivity differences are purely shaped by the productivity of the composite factor at stage n. Iterating (24), the optimal path of production solves:

$$\boldsymbol{\ell}^{j} = \arg\min_{\boldsymbol{\ell} \in \mathcal{J}^{N}} p^{F}_{j}(\boldsymbol{\ell}) = \arg\min_{\boldsymbol{\ell} \in \mathcal{J}^{N}} \left\{ \prod_{n=1}^{N} \left(a^{n}_{\ell(n)} c^{n}_{\ell(n)}\right)^{\alpha_n \beta_n} \right\}, \tag{25}$$

where:

$$\beta_n \equiv \prod_{m=n+1}^{N} (1 - \alpha_m), \tag{26}$$

and where we use the convention $\prod_{m=N+1}^{N}(1-\alpha_m) = 1$. In equation (25), while α_n is the cost share of the stage-n composite factor in stage-n production, $\alpha_n \beta_n$ is the cost share of this same stage-n composite factor in the *whole* global value chain (note that $\sum_{n=1}^{N} \alpha_n \beta_n = 1$).

As is clear from equation (25), we can break the cost-minimization problem into a sequence of N independent cost-minimization problems in which the optimal location of stage n is simply given by $\ell^{j}(n) = \arg\min_{\boldsymbol{\ell}(n) \in \mathcal{J}} \left\{a^{n}_{\ell(n)} c^{n}_{\ell(n)}\right\}$, and is thus independent of the country of consumption j. It then becomes evident that the assignment of stages to countries is independent of the positioning of stages in the value chain and depends solely on standard relative production cost considerations, as in standard neoclassical trade theory. For instance, if the local composite factor is labor, there are a continuum N of stages, there are only two countries, and all firms in a given country share the same technology, the general equilibrium of the model becomes completely isomorphic to the celebrated Ricardian model of trade in Dornbusch et al. (1977), and thus the assignment of stages to countries is shaped by comparative advantage. Similarly, if $a^n_{\ell(n)} = 1$ for all n and $\ell(n)$, but the local composite factor combines capital and labor with different capital intensities in different stages, then the framework becomes related to the multi-stage neoclassical model in Dixit and Grossman (1982), and again whether countries specialize upstream or downstream depends on the interaction of their physical capital abundance and the factor intensity of various stages, regardless of the positioning of stages in the value chain.

Free Trade: Absolute Advantage. To introduce a role for sequentiality, we now turn to a variant of (24) inspired by the work of Costinot et al. (2013), who in turn build on the insights from Kremer (1993). We now set $a^n_{\ell(n)} = 1$ and $c^n_{\ell(n)} = c_{\ell(n)}$ for all $n \in \mathcal{N}$ and $j \in \mathcal{J}$, but we allow TFP $z_{\ell(n)}$ to vary across countries. Standard trade theory would suggest that in the absence of comparative advantage differences across countries, the pattern of trade is indeterminate. Low TFP countries will face higher costs on account of their less efficient technologies, but in general equilibrium, their factor costs will adjust to equalize production costs across countries. Nevertheless, with sequential production matters are far less clear. In particular, iterating (24), the optimal path of production solves:

$$\boldsymbol{\ell}^j = \arg\min_{\boldsymbol{\ell} \in \mathcal{J}^N} p^F_j(\boldsymbol{\ell}) = \arg\min_{\boldsymbol{\ell} \in \mathcal{J}^N} \left\{ \prod_{n=1}^{N} \left(z_{\ell(n)} \right)^{-\beta_n} \left(c_{\ell(n)} \right)^{\alpha_n \beta_n} \right\}, \tag{27}$$

where β_n is defined in equation (26). As in our case above, we can again break the cost-minimization stage by stage, and simply solve $\ell^j(n) = \arg\min_{\boldsymbol{\ell(n)} \in \mathcal{J}} \left\{ \left(z_{\ell(n)} \right)^{-1/\alpha_n} c_{\ell(n)} \right\}$. Note then that whether absolute TFP differences disproportionately affect upstream or downstream stages depends crucially on whether value added intensity α_n rises or falls along GVCs. Costinot et al. (2013) develop a framework in which α_n effectively falls along the value chain, and thus conclude that absolute productivity differences across countries shape the specialization of countries in GVCs, with more efficient countries specializing in downstream stages of production. Although we will not solve for the general equilibrium of the model, it should be clear that if we focus on the case in which $c_{\ell(n)} = w_{\ell(n)}$ (so the composite factor is just labor), there are a continuum of stages and only two countries, the model reduces to the Dornbusch et al. (1977) framework with a monotonic relative efficiency schedule that confers comparative advantage in downstream stages to high-TFP countries, whenever α_n falls with n.

Costly Trade. We now consider an environment with costly trade, following the approach in Antràs and de Gortari (2020). For simplicity, we set $z_{\ell(n)} = a^n_{\ell(n)} = 1$ for all $n \in \mathcal{N}$ and $j \in \mathcal{J}$, and iterating (24), the lead-firm problem reduces to:

$$\boldsymbol{\ell}^j = \arg\min_{\boldsymbol{\ell}\in\mathcal{J}^N} p_j^F(\boldsymbol{\ell}) = \arg\min_{\boldsymbol{\ell}\in\mathcal{J}^N} \left\{ \prod_{n=1}^{N} \left(c^n_{\ell(n)}\right)^{\alpha_n\beta_n} \times \prod_{n=1}^{N-1} \left(\tau_{\ell(n)\ell(n+1)}\right)^{\beta_n} \times \tau_{\ell(N)j} \right\}, \tag{28}$$

where β_n is again given in (26). Antràs and de Gortari (2020) emphasize two features of this problem. First, for general bilateral trade costs, a lead firm can no longer perform cost minimization independently stage by stage, and instead it needs to optimize over the whole path of production. Intuitively, the location $\ell(n)$ minimizing production costs $c^n_{\ell(n)}$ might not be part of a firm's optimal path if the optimal locations for stages $n-1$ and $n+1$ are sufficiently far from $\ell(n)$. A direct implication of this result is that the presence of arbitrary trade costs turns a problem of dimensionality $N \times J$ into J much more complex problems of dimensionality J^N each. As Antràs and de Gortari (2020) and Tyazhelnikov (2019) show, however, as long as technologies feature constant returns to scale, the *lead firm* can break the problem into a series of stage- and country-specific optimal sourcing problems, and then solve the problem via forward induction (starting in the most upstream stage), thereby solving the problem for all possible destinations j with just $J \times N \times J$ computations.

A second noteworthy aspect of the minimand in equation (28) is that the trade-cost elasticity β_n of the unit cost of serving consumers in country j increases along the value chain. The reason for this compounding effect of trade costs stems from the fact that the costs of transporting goods are (naturally) modeled as being proportional to the gross value of the good being transacted. Thus, as the value of the good rises along the value chain, so does the amount of resources used to transport the goods across locations. An implication of this compounding effect is that, in choosing their optimal path of production, firms will be more concerned about reducing trade costs in relatively downstream stages than in relatively upstream stages. Antràs and de Gortari (2020) explore conditions under which this force generates a positive link between downstreamness and centrality, and building on the upstreamness measure in Antràs et al. (2012) and standard measures of centrality, they provide evidence for the existence of this relationship in the data.

We should briefly acknowledge other work featuring sequential production and costly trade. We have already mentioned above the work of Tyazhelnikov (2019), which was developed independently from Antràs and de Gortari (2020). The work of Fally and Hillberry (2018) also incorporates trade costs, though in a more rudimentary manner, and is largely focused on delineating firm boundaries, so we will return to it in Section 5.3. Much more relevant is the earlier work of Harms et al. (2012) and Baldwin and Venables (2013) who both study two-country models in which the presence of costly trade in environments where relative production costs (i.e., comparative advantage) does not rise or fall monotonically along production chains can generate interesting patterns of collocation.

Scale Economies. Our discussion above has focused on the case in which technologies feature constant returns to scale. When solving for a lead-firm problem this is far from an innocuous assumption, especially in the presence of costly trade. In fact, it is fair to say that the literature has struggled to find a tractable way to incorporate increasing returns to scale and trade costs in models of sequential GVCs. In Online Appendix B.5, we illustrate some of the complications that have hindered progress and also report on some preliminary progress.

5.2.2 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 only local factors of production are used. Unlike in models of exporting, however, lead firms are not restricted to produce 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 Volume 4 of this *Handbook* (see Antràs and Yeaple, 2014, in particular, Section 6.1). For this reason, and given space constraints, we relegate a review of some key recent contributions and insights from this literature to Online Appendix B.6.

5.2.3 Taking Stock

In sum, a growing literature is developing tools to better capture the complex operational decisions of large firms organizing GVCs. Progress in this branch of the literature has however been hampered by data availability and by computational complexity.

On the data front, testing models of the decisions of lead firms requires data on the operations of firms in more than one country, and thus standard sources used by trade economists, such as customs data or industrial census datasets are not suitable for this goal. Nevertheless, progress has been made by either exploiting survey data on the outward operations of multinational firms, and also by industry-specific studies relying on more granular data for specific sectors, such as the car industry in Head and Mayer (2019).

On the computational front, lead firms face highly complex decisions when designing their supply chains. The economics literature has largely been focused on finding suitable environments in which these decisions can be qualitatively characterized or computationally simplified, but it is hard to envision at this point that this agenda will lead to successful unified quantitative models of the decisions of lead firms. Our sense is that, sooner or later, this literature will need to close the gap with the parallel literature in supply chain management in the Operations Research field, which has long adopted heuristic methods to guide the optimal design of supply chains (see Vidal and Goetschalckx, 1997, for a review).

5.3 Organizing Relational GVCs

Although the research reviewed in the last few sections has provided valuable novel insights regarding the emergence and implications of GVCs, modeling global production sharing as simply an increase in the extent to which intermediate inputs are exported or imported (or to which multinationals set up foreign export platforms) misses important distinctive characteristics of the recent rise of GVCs. Three of these distinctive features are particularly important.

First, finding suitable suppliers of parts and components or suitable buyers of one's products is costly, or in economic lingo, there are search frictions. As a result, the fixed costs of exporting and importing we have been referring to in previous sections are better understood as sunk costs, which naturally create a "stickiness" among participants in a GVC.

Second, GVC participants often undertake numerous relationship-specific investments (such as purchasing specialized equipment or customizing products) which would obtain a much-depressed return were GVC links to be broken. The need to customize inputs adds to search frictions in creating a "lock-in" effect that further contributes to tie together the different agents in a GVC.

Third, the prevalence of lock-in effects within GVCs is made particularly relevant by the limited contractual security governing transactions within these chains. There are in turn two reasons why GVC participants perceive contractual insecurity. On the one hand, GVCs often involve transactions for which a strong legal environment is particularly important to bind producers together and to preclude technological leakage. On the other hand, GVCs often flow into countries with weak contracting institutions that do not offer the same contractual safeguards that typically accompany similar exchanges occurring in rich countries. As a result, GVC participants are often left to employ repeated interactions among them to build a governance that provides implicit contract enforcement. As in the case of matching frictions and relationship-specificity, this force contributes to the "stickiness" of GVC links. In sum, GVC *relationships* matter, and thus this branch of this literature has come to be referred to as studying *relational GVCs*.

In this section, we will briefly overview theoretical work that has attempted to shed light on the workings of relational GVCs. Before diving in, we should stress that we focus on recent developments; for earlier work on contractual frictions and firm boundary choices in international trade contexts, we refer readers to Chapter 2 of Volume 4 of this *Handbook* (see Antràs and Yeaple, 2014, in particular, Section 7).

5.3.1 Contractual Frictions and Firm Boundaries in Spiders

Let us return to the model of backward GVC participation developed in Section 5.1.2, in which final-good varieties are nontradable, but intermediate inputs can be traded across borders. Chor and Ma (2020) embed a property-rights model of firm boundaries à la Antràs (2003) and Antràs and Helpman (2004) into this framework. More specifically, the following new assumptions are made (mathematical details are relegated to Online Appendix B.7). First, each input variety is produced combining headquarter services and a manufacturing input provided by the supplier according to a Cobb-Douglas technology. Second, both headquarter services and the supplier input are relationship-specific in the sense that they are each customized as inputs 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. For these non-contractible investments, one needs to specify how the terms of exchange will be determined ex-post, once all investments have been incurred. Fourth, 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 of the surplus from the relationship, with this surplus in turn related to the contribution of all the other suppliers into production. This share 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 of surplus that is higher than the share 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 should be correlated, Chor and Ma (2020) assume that overall productivity is drawn from a "nested-Fréchet" distribution (see Online Appendix B.7 for details). This specification delivers a closed-form expression for sourcing shares that has an intuitive nested logit form: The share of inputs obtained from a given country j under (say) integration is equal to the share sourced from country j, multiplied by the share sourced under integration conditional on having chosen country j. 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 and the bargaining parameters.

Chor and Ma (2020) 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 then 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.

Although we have highlighted the work of Chor and Ma (2020), it is worth closing this subsection by outlining recent work that has similarly explored how contractual frictions shape the sourcing decisions of firms, and how those decisions in turn shape the consequences of trade integration or of changes in the contractual environment. Many of the early contributions to this literature – which focused on low-dimensional models – are overviewed in Antràs and Yeaple (2014) and Antràs (2016). The work of Boehm (2020) and Boehm and Oberfield (2020) is much closer in spirit to the work of Chor and Ma (2020) in that they also provide welfare assessments of contracting frictions, with Boehm (2020) in particular doing so in a full multi-country, multi-sector general equilibrium setting. That said, contracting frictions in these papers are modeled based on transactions-cost theory, in situations in which the firm-supplier relationship features a one-sided (rather than bilateral) holdup problem.

5.3.2 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 by 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. We relegate all mathematical details to Online Appendix B.8.

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 $i \in [0, 1]$, with a larger i corresponding to stages further downstream and thus closer to the finished product; the stage inputs feature a symmetric degree of substitutability.

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: 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 i, independently from the bilateral negotiations that take place at other stages.[47] 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.

Exploiting the recursive structure of the model, Antràs and Chor (2013) characterize the optimal

[47] See Antràs and Chor (2013) for alternative formulations of the bargaining protocol.

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 governs whether the incentive for the final-good producer to retain a larger surplus share increases or decreases along the value chain. When final goods are more substitutable than inputs, input investments are sequential complements, and integration of upstream stages is particulary costly because it reduces the incentives to invest not only of these early suppliers but also of all suppliers downstream. Conversely, when final goods are less substitutable than inputs, investments are sequential substitutes, and outsourcing of upstream stages is now relatively detrimental, since it reduces 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 of the model, and successfully test these predictions by combining information on firms' production activities in more than 100 countries with upstreamness measures computed from input-output tables. In largely contemporaneous work, Fally and Hillberry (2018) developed an alternative framework – building on work by Kikuchi et al. (2018) – illustrating the consequences of contractual frictions for the location and organization of GVCs. Fally and Hillberry (2018) demonstrate that their framework delivers a positive relationship between a country-industry pair's upstreamness and its gross-output-to-value-added ratio, and they provide empirical evidence consistent with this.

5.3.3 Search Frictions and Relational Contracting

Beyond frictions associated with incomplete contracting, the literature on the international organization of production has also stressed the role of search frictions and relational contracting in shaping the emergence and sustainability of GVC links. Due to space constraints, and the fact that some of these papers were reviewed in Antràs and Yeaple (2014), we relegate a discussion of these contributions to Online Appendix B.9.

6 Trade Policy in the Age of GVCs

Relative to the work on the measurement and modeling of GVCs, our profession's understanding of the policy implications of the rise of GVCs is much less developed. How does the use of traditional instruments of trade policy – tariffs, quantitative restrictions, or regulatory standards – affect the volume of trade and social welfare in a world of GVCs relative to a world where trade is exclusively in final goods? How does the rise of GVCs affect our understanding of what constitutes optimal trade policy? Answers to these questions are particularly relevant in current times, when trade policy discussions are as salient as they have been in the last fifty years.

We will structure the discussion along the following main themes. In Sections 6.1-6.3, we review work on the implications and optimal design of trade policy in competitive environments featuring final-good trade as well as intermediate-input trade. In Section 6.4, we study the role of political economy forces in shaping the structure of protection in upstream and downstream markets. We extend the analysis to richer frameworks, such as frameworks that distinguish between domestic and foreign value added in production (Section 6.5), general equilibrium Ricardian models featuring product differentiation in upstream and downstream markets (Section 6.6), models featuring imperfect competition (Section 6.7), and models of relational GVCs (Section 6.8).

Although we will connect at times with selected empirical papers, the focus of this section is admittedly theoretical in nature. In recent years, a number of interesting empirical papers have been developed to study the implications of trade protection for the geography of GVCs (Conconi et al., 2018; Vandenbussche and Viegelahn, 2018; Bown et al., 2020; Barattieri and Cacciatore, 2020; Flaaen and Pierce, 2019; Handley et al., 2020).

6.1 Effective Rate of Protection and Tariff Escalation

As in the rest of this survey, our focus is largely on work carried out (roughly) in the last ten years, but we begin with an overview of some leading themes in the older trade policy literature that are very much relevant to intermediate input trade and to GVCs.

Consider first the literature on effective rates of protection, which is exemplified by the seminal work of Corden (1966). This literature is concerned with the implications of intermediate input trade for the incidence of import tariffs. More precisely, 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). In Online Appendix C.1, we formally study this concept, and derive Corden's result that the effective rate of protection exceeds "nominal" rates of protection whenever import tariffs on final goods are higher than import tariffs on inputs, or whenever the tariff structure features "tariff escalation".

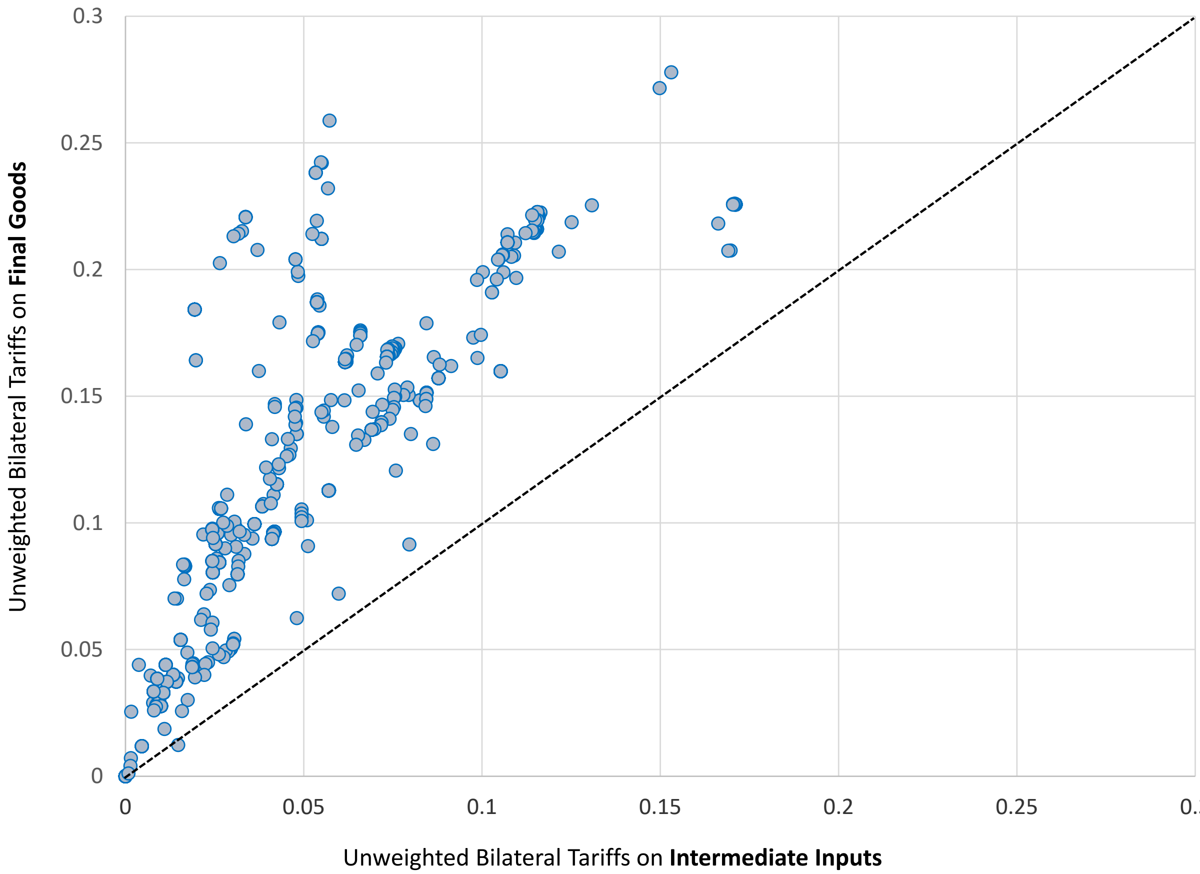
Tariff escalation has been documented in a large number of studies, from the early work by Travis (1964) and Balassa (1965, 1971), to the more recent calculations by Bown and Crowley (2016) and Shapiro (2021). To illustrate this phenomenon, Figure 6 depicts applied bilateral tariffs on final goods versus intermediate inputs for 37 countries, as computed by Shapiro (2021), where the distinction between a final good and an input is drawn based on the UN BEC end-use classification. As is clear from the figure, all but one of the scatter points are above the 45-degree line, and in many cases by a wide margin. Shapiro (2021) also finds a smoother negative correlation between tariffs and the upstreamness of a sector, as measured by Antràs et al. (2012).

The existence of a clear pattern of tariff escalation explains why effective rates of protection appear larger than nominal rates of protection on final goods. This still leaves open the question of what the policy relevance of this finding is. Are high effective rates of protection bad for economic welfare? Is tariff escalation consistent with the tariffs on final goods and on inputs that a social planner would set? The next sections will attempt to provide tentative answers to these questions.

6.2 Baseline: A Simple Roundabout Model

We begin by analyzing optimal trade policy in a partial-equilibrium, constant returns-to-scale, perfectly competitive environment with roundabout input-output links. The framework builds on

Figure 6: Tariff Escalation



Cadot et al. (2004) and Gawande et al. (2012) – who themselves extend the classical Grossman and Helpman (1994) "protection for sale" model – but we relax their assumption of the country under study being a small open economy, and for now we do not model political economy biases.

We consider a two-country environment with a Home country, the focus of the analysis, and a Foreign one, which we sometimes refer to as the Rest of the World (RoW). The Home country is populated by a continuum of measure 1 of individuals with identical quasi-linear preferences:

$$U(c) = c_0 + \sum_{s=1}^{S} u_s(c_s),$$

where c_0 denotes consumption of the outside numéraire good, which is costlessly traded and not subject to tariffs. Within each "outside" sector s, Home and Foreign goods are assumed to be perfect substitutes.

On the supply side, the numéraire good is produced one-to-one with labor, which pins down the wage rate to 1 in all countries. Non-numéraire goods are produced combining labor, sector-specific capital, and the intermediate inputs consisting of output from all other sectors of the economy. To simplify matters, and following Cadot et al. (2004) and Gawande et al. (2012), we assume that inputs are used in fixed proportions, so we can write the rent function $\Pi_s(p_s)$ for the capital specific to sector s as:

$$\Pi_s(p_{1,\ldots},p_S) = \left(p_s - \sum\nolimits_{r=1}^{S} a_{rs}p_r\right) x_s(k_s,\ell_s) - \ell_s, \tag{29}$$

where x_s is output in sector s, a_{rs} is the fixed requirement of units of good r used as inputs in producing good s, k_s is the fixed amount of sector-specific capital in sector s, and ℓ_s is the amount of labor hired in sector s.

Due to the quasi-linearity of preferences, we can write Home welfare associated with a given vector $\mathbf{p} = (p_{1,\ldots},p_S)$ of domestic prices and a given vector $\mathbf{p}^* = \left(p^*_{1,\ldots},p^*_S\right)$ of foreign prices as:

$$W(\mathbf{p},\mathbf{p}^*) = 1 + \sum_{s=1}^{S}\Pi_s(\mathbf{p}) + \sum_{s=1}^{S} S_s(p_s) + \sum_{s=1}^{S}(p_s - p^*_s)\left(c_s(p_s) + \sum\nolimits_{r=1}^{S} a_{sr}x_r(\mathbf{p}) - x_s(\mathbf{p})\right), \tag{30}$$

where $S_s(p_s)$ is consumer surplus in sector s, and where the last term in parentheses is Home's imports in sector s, or:

$$m_s(\mathbf{p}) \equiv c_s(p_s) + \sum\nolimits_{r=1}^{S} a_{sr}x_r(\mathbf{p}) - x_s(\mathbf{p}).$$

Welfare in the Foreign country can be expressed in an analogous manner.

We next 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 and re-arranging the first-order conditions (see Online Appendix C.2), we obtain the following optimality condition:

$$\sum_{r=1}^{S}\frac{\partial p^*_r}{\partial t_s}m^*_r(\mathbf{p}^*) = \sum_{r=1}^{S}(p_r - p^*_r)\sum_{t=1}^{S}\frac{\partial m^*_r(\mathbf{p}^*)}{\partial p^*_t}\frac{\partial p^*_t}{\partial t_s}. \tag{31}$$

If one were to ignore cross-price effects on import volumes, this formula would reduce to the familiar inverse export supply elasticity optimal tariff equation. Nevertheless, with vertical linkages across countries, there will naturally be cross-price effects on the supply side, which will generate cross-price effects on net import volumes, even when one shuts down cross-price effects on the demand side, as we have done with our assumption of separable quasi-linear preferences. We can of course still re-define (31) as:

$$(d\mathbf{p})(m^*(\mathbf{p}^*))^T = (\mathbf{p} - \mathbf{p}^*)(d\mathbf{m}^*)^T,$$

which then equates tariffs with a "general-equilibrium" inverse export supply elasticity. In practice, however, this is not an elasticity that is straightforward to estimate, so this general formula provides little guidance in assessing whether the observed structure of protection is in line with the one maximizing social welfare. To make progress on this issue, we next turn to a special case of this general model.

6.3 Tariffs on Final Goods and on Inputs in Competitive Economies

Let us consider the same environment as before, but assume now that there are only two sectors, other than the outside good sector 0. The first sector F produces a good that is only consumed as a final good, while the second sector I produces a good that is only used as an input in production.[48] This simplified setting allows one to gain some insights on how intermediate input trade affects optimal final-good tariffs, and also what determines the optimal structure of protection in intermediate-input sectors. More specifically, in Online Appendix C.3, we obtain that Home's optimal final-good and input tariffs t_F and t_I must satisfy:

$$1 = (t_F - 1)\,\varepsilon^*_{F,X} + (t_I - 1)\,\frac{1}{m^*_F(\mathbf{p}^*)}\frac{\partial m^*_I(\mathbf{p}^*)}{\partial p^*_F}, \text{ and} \tag{32}$$

$$1 = (t_F - 1)\,\frac{1}{m^*_I(\mathbf{p}^*)}\frac{\partial m^*_F(\mathbf{p}^*)}{\partial p^*_I} + (t_I - 1)\,\varepsilon^*_{I,X}, \tag{33}$$

where $\varepsilon^*_{F,X}$ and $\varepsilon^*_{I,X}$ are the sectoral foreign export supply elasticities, and where $\partial m^*_I(\mathbf{p}^*)/\partial p^*_F$ and $\partial m^*_F(\mathbf{p}^*)/\partial p^*_I$ are necessarily non-negative terms (see Online Appendix C.3).

These expressions make it clear that the presence of vertical linkages introduces a wedge relative to the standard formula linking sectoral optimal tariffs to sectoral inverse foreign export supply elasticities. The sign and size of this wedge depends however on subtle aspects of the environment, such as whether Home is a net exporter or a net importer of each of the types of goods. We discuss the different possible cases and intuition behind the wedges in Online Appendix C.3, but the bottomline is that in perfectly competitive environments with homogeneous goods, one does not obtain sharp predictions on the relative size of input versus final-good tariffs or on whether final-good tariffs are higher or lower in a world with GVCs.

6.4 Political Economy, Lobbying Competition and Tariff Escalation

We next revert back to the roundabout model with general input-output links and consider the role of political economy forces in shaping the structure of protection in a world of GVCs. As microfounded in the work of Grossman and Helpman (1994), we posit that policy makers choose tariffs to maximize a "policy support function" of the type:

$$W(\mathbf{p}, \mathbf{p}^*) + \lambda \sum_{s=1}^{S} \Pi_s(\mathbf{p}),$$

where $W(\mathbf{p}, \mathbf{p}^*)$ is social welfare in equation (30), and $\lambda > 0$ is an additional weight put on producer surplus. This latter term reflects the notion that concentration in the ownership of the sector-specific types of capital used in production allows producers to solve the collective action problem inherent in lobbying for protection, while consumers remain unorganized and ineffective in fighting producers'

[48] Other work studying optimal tariffs on final goods and inputs in neoclassical environments includes Ruffin (1969), Casas (1973), and Das (1983).

demands for protection. To isolate the role of political forces, we follow Grossman and Helpman (1994), Cadot et al. (2004), and Gawande et al. (2012), and assume now that Home is a small open economy. Under this assumption, and regardless of the structure on input-output links, a social planner would choose free trade in all sectors, as is clear from equation (31), where $p_s = p_s^*$ for all s whenever $\partial p_r^*/\partial t_s = 0$ for all r and s.

In the presence of these political-economy forces, the system of first-order conditions characterizing optimal tariffs can be expressed as:

$$\sum_{r=1}^{S} (p_r - p_r^*) \frac{\partial m_r(\mathbf{p})}{\partial p_s} + \lambda \left(x_s - \sum_{r=1}^{S} a_{sr} x_r \right) = 0. \tag{34}$$

The interpretation of the two terms in equation (34) is as follows. The first term is analogous to the last term in the general expression (31), but it is somewhat simpler because one need not worry about tariff revenue effects working through changes in prices in other sectors. The second term is more novel and reflects the competition between sector-specific interests. As in Grossman and Helpman (1994), other things equal, sectors with higher output levels (relative to import volumes) will achieve higher protection, but note that this effect is attenuated by the usage of these sector's output in other sectors. Intuitively, the more a sector's output is used as an input in other sectors, the higher will be the cost of protection in that sector for other sectors in the economy. Because these other sectors have a voice in the political process (or, more broadly, in the process of tariff formation), this counterlobbying will tend to reduce the level of protection. As indicated by Cadot et al. (2004), this implies that, other things equal, relatively downstream sectors that sell predominantly to consumers should achieve higher levels of protection than relatively upstream sectors that sell predominantly to other sectors. The authors view this prediction as providing a rationale for the phenomenon of tariff escalation, which as described in Section 6.1, has been widely documented in the literature (see Online Appendix C.4 for a more formal derivation of this result).

6.5 Value Added Approach

We next consider an environment inspired by the work of Blanchard et al. (2016). Although this is not essential for some of the results below, we stick to the competitive model developed in Section 6.3. The main novelty is that we now consider an environment in which production of final goods in each country combines labor, sector-specific capital, and an input that is *only* produced in the other country. From the point of view of the Home country, Blanchard et al. (2016) refer to the imported input as "Foreign Value Added" (or FVA) used in Home production, and to the exported input as "Domestic Value Added" (or DVA) in Foreign production.

Under these assumptions, Blanchard et al. (2016) show that the first-order condition associated with the choice of a tariff on the final good can be written as (see Online Appendix C.5 for details):

$$t_F - 1 = \frac{1}{\varepsilon_{F,X}^*} \left(1 - \frac{p_{IFor} x_{IFor}}{p_F^* m_F} \xi_{For} - \frac{p_{IDom}^* x_{IDom}^*}{p_F^* m_F} \xi_{Dom}^* \right), \tag{35}$$

where $\varepsilon^*_{F,X}$ is the standard export supply elasticity, ξ_{For} and ξ^*_{Dom} are positive terms, and where x_{IFor} is the Foreign input used in Home production, x^*_{IDom} is the Home input used in Foreign, and the corresponding prices for these inputs are p_{IFor} and p^*_{IDom}, respectively.

Equation (35) makes it clear that there are two terms that generate a wedge between the optimal final-good tariffs in a standard model without input trade, and in this model featuring foreign value added in domestic production and domestic value added in foreign production. These terms capture the intuitive nature that levying tariffs is more costly when (i) part of the rents obtained from that protection accrue to foreigners in the form of higher input prices p_{IFor}, and when (ii) the fall in the Foreign final-good price caused by the tariff reduces the rents that domestic value added obtains abroad (by reducing p^*_{IDom}). In sum, optimal final-good tariffs are predicted to be lower, the higher the foreign value added in domestic production (the term $p_{IFor}x_{IFor}$ in (35)), and the higher is the domestic value added in foreign production (the term $p^*_{IDom}x^*_{IDom}$ in (35)).

Blanchard et al. (2016) also explore the empirical validity of their theoretical predictions. To do so, they combine data on world input-output links from the WIOD, tariff data from the World Bank's WITS website, as well as data on temporary trade barriers from Chad Bown's Temporary Trade Barriers Database (Bown, 2014). They find evidence in support of their two key predictions both when looking at how countries discriminate across trading partners by lowering protection through bilateral tariff preferences, and also when countries discriminate by raising protection through the adoption of temporary trade barriers, particularly against China.

6.6 Product Differentiation and General Equilibrium

So far, we have restricted the analysis to partial-equilibrium environments in which wages are pinned down by an outside sector and in which goods are homogeneous. This creates a bit of disconnect with modern macro models of GVCs, which as we have seen in Section 4, tend to be general equilibrium in nature and generate bilateral gross exports and imports within sectors.

Beshkar and Lashkaripour (2020) study optimal tariffs in a general equilibrium environment with roundabout production in which goods are differentiated by their country of production. Although their underlying economic model is significantly more general, it is useful to focus attention on a discussion of their main results for the case in which their model reduces to the Caliendo and Parro (2015) framework. This amounts to assuming that: (i) labor is the only factor of production; (ii) preferences are Cobb-Douglas across sectors, and CES across differentiated varieties within sectors; and (iii) technology is Cobb-Douglas in labor and the bundle of inputs in various sectors, with the latter being a CES aggregator of the differentiated inputs.

Building on the tools developed by Costinot et al. (2015), Beshkar and Lashkaripour (2020) solve for optimal trade taxes at the sectoral level, with the same tax levels applying regardless of the end use (i.e., final good or input) of the good being traded. Their main results are as follows. First, Lerner symmetry applies in this framework, and thus the level of optimal import and export taxes is only determined up to a common multiplicative shifter $(1+\bar{t})$. Second, and in line with the results in Costinot et al. (2015), the presence of input-output linkages does not undo the fact that in

Ricardian economies, optimal input tariffs are uniform across sectors. Intuitively, the main goal of import tariffs in this environment is to improve the countries terms of trade, and because all sectors' technology is linear in labor, this implies that the incentive to mark-down imports is proportional in all sectors. On the other hand, optimal export taxes are heterogeneous across sectors. The reason for this is that the main goal of export taxes is to exploit Home's market power in the differentiated varieties it produces. This leads to a markup (e.g., an export tax) that is negatively related to the trade elasticity and to the own trade share in the RoW, as in the well-known formula developed by Gros (1987). More novel is their finding that export taxes should be lower in situations in which higher export prices are passed-through back to Home consumers, as when the goods being exported include a large share of inputs that are re-imported back into Home. Consequently, Beshkar and Lashkaripour (2020) conclude that optimal export taxes are lower in upstream sectors than in downstream sectors, and they are also lower in a world of GVCs than in a world without vertical linkages across sectors.

Beshkar and Lashkaripour (2020) also consider the relevant case in which export taxes are ruled out. In that case, import tariffs cease to be uniform across sectors, as they serve a second-best role in exploiting Home's market power in their export sectors. Consistent with the logic above, however, the incentive to levy import tariffs is *higher* in relatively upstream sectors, because the cost of the tariff is partly passed on to Foreign consumers in the form of higher export prices for the goods embodying those inputs. As a result, their framework delivers a form of tariff de-escalation that is inconsistent with the observed negative correlation between import tariffs and upstreamness observed in the real world. This may be interpreted as indicating that the type of political economy effects emphasized by Cadot et al. (2004) and Gawande et al. (2012) are key for rationalizing tariff escalation practices. An alternative explanation, however, is that the pattern of optimal tariffs may look quite different under different market structures. We next turn to further explore the latter possibility.

6.7 Imperfect Competition

It is well understood that the study of trade policy outside the paradigm of perfectly competitive models is complicated by the fact that the nature and even the sign of optimal trade taxes is sensitive to details of how imperfect competition is modeled (see Eaton and Grossman, 1986). At the same time, the trade literature has largely converged to a particular approach to modeling imperfect competition – along the lines of Krugman (1980) – so it seems natural to explore optimal trade policy in versions of that environment that incorporate intermediate input trade. As in Krugman (1980), the focus is on an environment with CES preferences within sectors, increasing returns to scale technologies featuring constant marginal costs, and monopolistically competitive environments.

In carrying out this analysis, one could in principle follow a partial equilibrium approach or a general equilibrium approach, very much in line with the dichotomy outlined above in perfectly competitive environments. The partial equilibrium approach to the study of trade policy in monopolistically competitive environments originates in the work of Venables (1987), where the focus is solely on trade in final goods. The framework in Venables (1987) eliminates terms of trade effects working through wages by specifying an outside sector that pins down wages in all countries. The focus is instead on how trade taxes (and import tariffs, in particular) can enhance welfare by relocating (final-good) firm entry into one's own country, something that may prove beneficial for consumers – despite higher prices for imported goods – due to the presence of trade costs.[49] The general equilibrium approach to optimal trade policy with monopolistic competition – best exemplified by the work of Gros (1987) – instead re-focuses attention on terms-of-trade effects, and emphasizes that small open economies may have market power whenever the goods they import and export are differentiated. In terms of relocation effects, these are entirely eliminated in the one-sector model in Gros (1987).

A nascent literature is currently exploring variants of these models that feature intermediate input trade, and highlights the novel forces that arise in that case. Two recent examples are Caliendo et al. (2021) and Antràs et al. (2021), who both consider multi-sector Ricardian economies featuring general equilibrium terms-of-trade forces, but also Venables-style production relocation effects.

The simplest version of Caliendo et al. (2021)'s framework considers an environment analogous to that in Gros (1987) but with production being roundabout in nature. With imperfect competition, producers charge a markup over their marginal cost when selling intermediate inputs. Because, when selling to consumers, firms also charge a markup over marginal cost, the model features a double-marginalization inefficiency, that is absent in models without input trade. This inefficiency can be undone with targeted domestic subsidies, but in their absence, Caliendo et al. (2021) show that there is a second-best rationale for setting import tariffs that are lower than without roundabout production. The authors interpret this result as suggesting that the rise of GVCs and intermediate input trade puts downward pressure on the incentives of countries to unilaterally set tariffs on their trading partners. In a quantitative exercise involving 186 countries, they also show that the magnitude of these mechanisms is sizeable, leading to a median optimal tariff of 10%, as compared to 27% in the absence of roundabout production.

Another recent contribution to this burgeoning literature is the work of Antràs et al. (2021). Rather than introducing intermediate input trade via roundabout production, these authors instead consider a two-sector version of the Krugman (1980) framework, with a novel intermediate-input sector which provides a bundle of differentiated input varieties to a Krugman-like final-good sector that produces differentiated consumer varieties, by combining labor and the bundle of intermediate input varieties. The other assumptions of the model (a unique primitive factor of production, CES aggregators, increasing returns-to-scale technologies, and monopolistic competition in both sectors) are all identical to those in Krugman (1980). This framework features the same type of double marginalization inefficiency highlighted by Caliendo et al. (2021), but the focus in Antràs et al. (2021) is instead to compare the differential incentives to levy import tariffs on final goods versus intermediate inputs. The equations characterizing these optimal tariffs are involved, but Antràs et al. (2021) develop a first-order approach to characterizing the various mechanisms (terms of trade

[49] Ossa (2011) further developed Venables (1987)'s analysis and built a theory of trade agreements based on it.

effects, production relocation effects, etc.) through which tariffs on final goods and inputs affect the general equilibrium of the model and welfare, and they also derive analytical results for the case of a small open economy. Their main result is that the optimal tariff is positive for both final goods and for inputs, but the optimal tariff is typically higher for final goods than for inputs. Furthermore, the optimal tariff on inputs is quantitatively very small when domestic subsidies are available to undo the double marginalization inefficiency, while the optimal tariff on final goods remains high. Antràs et al. (2021) interpret their results as a potential rationale for observed tariff escalation practices.

6.8 Trade Policy and Relational GVCs

We finally note that there exists a body of 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. This literature includes the work of Antràs and Staiger (2012), Ornelas and Turner (2008), and Grossman and Helpman (2020), among others. Due to space constraints, this literature is summarized in Online Appendix C.6.

7 Conclusion

Over the past few decades, production processes have become increasingly more complex in the world economy. Any finished good now typically embodies value added from multiple countries of origin, with this value added often crossing multiple borders en route to its point of consumption. In this article, we have surveyed recent developments and contributions by economists, particularly in the field of international trade, towards deepening our understanding of such "global value chains".

On the empirical side, we have reviewed efforts to measure GVCs as a "macro" phenomenon. Work on this front has advanced in recent years with improvements in World Input-Output Tables and the development of value added accounting methodologies. This has been accompanied by a parallel large body of empirical work on firms in international trade, which has uncovered useful facts at the "micro" level on selection into participation in GVCs, the formation of buyer-supplier links, and the relational nature of these ties.

On the theory side, we have attempted to organize the modeling frameworks that speak to various aspects of GVC activity. This includes "macro" models that incorporate rich input-output linkages across countries and industries, either in the form of a "roundabout" production setup or in sequential chains. Such models have provided valuable quantitative insights on the aggregate consequences of GVCs, relative to a world in which such input-output linkages are absent. On the other hand, a rich vein of "micro" models has shone the spotlight on the firm-level drivers of forward and backward participation in GVCs, as well as the relational aspects of these GVC links. Last but not least, we have surveyed a nascent body of work seeking to understand the trade policy implications of GVCs, particularly for the tariff escalation phenomenon.

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Global Value Chains

Pol Antràs and Davin Chor

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

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

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

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]

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

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

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:

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

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 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

[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 $\alpha_{j}^{s} = \sum_{i=1}^{J} F_{ij}^{s}/\left(w_{j}L_{j} + D_{j}\right)$.

conditions (A.5). In the counterfactual equilibrium, these can be re-written as:

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

and:

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

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 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,

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

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 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:

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

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

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 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

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

profit function for the final-good producer of the form:

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

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 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

[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).

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:

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

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:

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

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:

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

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 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

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

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):

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

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 $\lambda_i=1$

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

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).

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

[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.

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.

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

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

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:

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

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 $m_I^*(\mathbf{p}^*) = ax_F(\mathbf{p}^*) - x_I(\mathbf{p}^*)$ 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:

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

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

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

[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.

Welfare at Home is now given by:

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

where $\mathbf{p} = (p_F, p_{IFor})$ and $\mathbf{p}^* = (p^*_F, p^*_{IDom})$. 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 $x_F(p_F)$.

We next consider the effects of levying an import tariff t_F on the final good. Differentiating $W(\mathbf{p},\mathbf{p}^*)$ with respect to t_F and invoking $m_F(\mathbf{p}) = -m^*_F(\mathbf{p})$ 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 $y(x)$, with $y(0) = 0$, $y'(x) > 0$, $y''(x) < 0$, $\lim_{x\to 0} y'(x) = +\infty$, and $\lim_{x\to\infty} y'(x) = 0$. 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 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.

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

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:

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

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]

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

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

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]

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

[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.

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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