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Measuring Global Value Chains

Robert C. Johnson[1,2]

[1]Department of Economics, Dartmouth College, Hanover, New Hampshire 03755, USA; email: robert.c.johnson@dartmouth.edu

[2]National Bureau of Economic Research, Cambridge, Massachusetts 02138, USA

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Abstract

Recent decades have seen the emergence of global value chains (GVCs), in which production stages for individual goods are broken apart and scattered across countries. Stimulated by these developments, there has been rapid progress in data and methods for measuring GVC linkages. The macro approach to measuring GVCs connects national input–output tables across borders by using bilateral trade data to construct global input–output tables. These tables have been applied to measure trade in value added, the length of and location of producers in GVCs, and price linkages across countries. The micro approach uses firm-level data to document firms' input sourcing decisions, how import and export participation are linked, and how multinational firms organize their production networks. In this review, I evaluate progress in these two approaches, highlighting points of contact between them and areas that demand further work. I argue that further convergence between these approaches can strengthen both, yielding a more complete empirical portrait of GVCs.

1. INTRODUCTION

Recent decades have seen the emergence of global value chains (GVCs), in which production stages for individual goods are broken apart and scattered across countries. Examples of this phenomenon are everywhere—from the production process for Apple iPhones to those of Nutella hazelnut spread, Boeing airplanes, New Balance running shoes, and so on. Hints of this GVC activity are easy to see in trade data, as well. For example, multinational firms are involved in more than 90% of US trade, the share of imported inputs in total materials use has risen steadily around the world, and China has become the world's factory by providing incentives for the production of exports with imported inputs.

Notwithstanding these anecdotes and scattered statistics, researchers have struggled to develop a coherent empirical portrait of GVCs. One reason for this is that the national accounts were not built for the task of measuring GVCs. While input–output accounts provide a rich description of value chain linkages across industries within a given country, they stop at the border: They contain no information on how exports are used abroad, and they do not tell us anything about how imported goods are produced. Similarly, firm census and customs data contain important details about firm-level input sourcing and export participation and, thus, the backward and forward engagement of individual firms in GVCs. However, they do so for one country or firm piece of the value chain at a time. At both the macro (input–output) and micro (firm) levels, conventional data sources lack the information needed to map out the entire global production process and measure GVC linkages.

Addressing gaps in the measurement of GVCs is important both for advancing our understanding of how the modern global economy works and for addressing policy questions. Starting with positive concerns, GVCs influence the response of trade to frictions and may amplify gains from trade; they also change the nature of macrospillovers across countries. At the micro level, offshoring (one manifestation of GVC participation) is central to explaining firm performance and labor market outcomes. From a normative perspective, GVCs alter government incentives to impose trade protection and have implications for optimal monetary policy in the open economy. Furthermore, policy makers are already devoting significant attention to devising new approaches to measuring GVCs and sorting out their policy implications (see, e.g., U. N. Econ. Comm. Eur. 2015, World Bank 2017, World Trade Organ. & Inst. Dev. Econ. Jpn. Extern. Trade Organ. 2011).

Fortunately, important progress has been made in measuring GVCs on two fronts. First, on the macro level, researchers have pushed to extend the input–output accounting apparatus across borders, using disaggregate trade data to link existing national input–output tables across countries.[1] The resulting global input–output tables describe from whom each industry sources inputs from around the world and to whom each industry's output is sold at home or abroad, whether as inputs to downstream industries or to final end users. At the micro level, recent research has also devoted increased attention to documenting firms' input sourcing decisions, how importing is connected to exporting at the firm level, and how multinational firms organize their production networks.

In this review, I argue that these complementary research tracks are proceeding toward a more complete description of GVCs. In Section 2, I start by describing how global input–output data

[1] Although research on global (linked multicountry) input–output tables has flourished in recent years, the basic ideas are not new. The conceptual origins of global input–output tables date back to work on many-region input–output models by Hollis Chenery, Walter Isard, Wassily Leontief, and Leon Moses in the 1950s. Regional input–output analysis continues to be a staple of the regional science literature (see Miller & Blair 2009, chapter 3). Furthermore, Leontief (1974) describes United Nations efforts to build global input–output tables in his Nobel Prize Lecture.

can be applied to measure the value-added content of trade, the length of GVCs and the location of producers within them, and price linkages across countries. By collecting these results in one place, I aim to clarify the links between them. In at least one instance, I extend existing results: In Section 2.2.2, I provide a new value-added decomposition of gross exports. I also briefly describe recent work that uses global input–output data to calibrate trade and macroeconomic models, and I discuss strengths and weaknesses of available data sources. Turning to firm-level data in Section 3, I survey recent work on offshoring and input sourcing, joint participation exporting and importing, and trade within multinational firms.

Along the way, I emphasize points of contact between the macro and micro approaches to measuring GVCs, building on the idea that aggregate input–output tables can (in principle, if not in practice) be constructed by aggregating firm-level transactions data. Furthermore, while the focus of this review is primarily on measurement of GVCs, I also address the theory of GVCs where theory and measurement are connected to one another.[2] In Section 4, I conclude the review by arguing that convergence between the macro and micro approaches to measuring GVCs can strengthen both, and I highlight areas in which theory and measurement remain far apart.

2. A MACRO (INPUT–OUTPUT) VIEW OF GLOBAL VALUE CHAINS

This section describes the input–output approach to measuring GVC linkages, which provides a macro-level view of GVCs. I begin by presenting two building blocks of the input–output approach, and I then discuss how they can be applied to measure trade in value added, characteristics of value chains, and price linkages. As a complement to this measurement work, I discuss how input–output data have been applied to calibrate trade and macroeconomic models. The section concludes with a review of data sources, in which I evaluate strengths and weaknesses of existing data.

2.1. Input–Output Preliminaries

Starting from the ground up, there are two basic building blocks of an input–output system. The first is an accounting relationship that describes how gross output from each country ($i, j \in \{1, 2, \ldots, N\}$) and industry ($s \in \{1, \ldots, S\}$) is used by final or intermediate purchasers, as in $y_i(s) = \sum_j f_{ij}(s) + \sum_j \sum_{s'} z_{ij}(s, s')$, where $y_i(s)$ is the value of gross output in industry s of country i, $f_{ij}(s)$ is the value of final goods shipped from industry s in country i to country j, and $z_{ij}(s, s')$ is the value of intermediates from industry s in country i used by industry s' in country j. The second is an accounting relationship that defines value added, i.e., value added in country i and sector s, denoted $v_i(s)$, equals the value of output less inputs used in production: $v_i(s) = y_i(s) - \sum_j \sum_{s'} z_{ji}(s', s)$.

These industry-by-industry and country-by-country output accounting equations can be stacked to form the global input–output system. Specifically, stack output into vector $\mathbf{y}$, with $(S \times 1)$-dimensional block elements $\mathbf{y}_i$, collect intermediate shipments into matrix $\mathbf{Z}$ with $(S \times S)$-dimensional block elements $\mathbf{Z}_{ij}$, arrange final goods shipments into $(NS \times N)$-dimensional matrix $\mathbf{F}$ with $(S \times 1)$-dimensional block elements $\mathbf{f}_{ij}$, and put value added into vector $\mathbf{v}$ with $(S \times 1)$-dimensional block elements $\mathbf{v}_i$. Following convention, define a global input–output matrix $\mathbf{A} = \mathbf{Z}\hat{\mathbf{y}}^{-1}$, with block elements $\mathbf{A}_{ij} = \mathbf{Z}_{ij}\hat{\mathbf{y}}_j^{-1}$, where $\hat{\mathbf{x}}$ denotes a diagonal matrix with vector $\mathbf{x}$

[2] Due to space constraints, I also do not extensively discuss quantitative or empirical results on the causes and consequences of the rise of GVCs (e.g., the determinants of value chain fragmentation, the consequences of offshoring for labor markets, or welfare gains from trade with GVCs). I touch on these issues only briefly to illustrate how better measurement is enabling progress in addressing them.

along the diagonal. The global input–output system can then be written concisely as

$$\mathbf{y} = \mathbf{A}\mathbf{y} + \mathbf{F}\boldsymbol{\iota} \tag{1.}$$

and

$$\mathbf{v}' = \mathbf{y}' - \boldsymbol{\iota}'\mathbf{A}\hat{\mathbf{y}}, \tag{2.}$$

where $\boldsymbol{\iota}$ denotes a conformable vector of ones (the dimension of which differs depending on the context).

2.2. Trade in Value Added

This section provides an overview of how input–output tables have been used to study trade in value added. I begin by presenting two value-added decompositions of final goods, which provide complementary perspectives on how value added is traded on the consumption versus production sides of the economy. I then discuss the value-added content of gross exports, presenting a new decomposition of export content in the process. For clarity's sake, I explain the main points in this section using a two-country input–output system, and I comment on additional issues that arise in many-country frameworks where appropriate.

2.2.1. Value-added content in final goods. Using Equation 1, the amount of gross output needed to produce final goods can be computed as

$$\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix} = [\mathbf{I} - \mathbf{A}]^{-1}\mathbf{F}\iota, \tag{3.}$$

where $[\mathbf{I} - \mathbf{A}]^{-1}$ is the Leontief Inverse of the global input–output matrix. For any given vector of final goods $\mathbf{f}$, the calculation $[\mathbf{I} - \mathbf{A}]^{-1}\mathbf{f}$ returns the vector of gross output (from all countries and industries) that is needed to produce those final goods, including both the value of the final goods themselves and all the intermediate inputs that are (directly or indirectly) used in producing those final goods. Value added embodied in $\mathbf{f}$ is then given by $\hat{\mathbf{v}}\hat{\mathbf{y}}^{-1}[\mathbf{I} - \mathbf{A}]^{-1}\mathbf{f}$, where $\hat{\mathbf{v}}\hat{\mathbf{y}}^{-1}$ is a matrix with value added–to-output ratios along the diagonal.

Equation 3 can be used to measure trade in value added from two complementary perspectives. First, final goods shipments can be decomposed based on the location in which they are consumed. Alternatively, final goods shipments can be decomposed based on the location in which they are produced. That is, mechanically, $\mathbf{F}\iota$ can be decomposed in either of the following two ways:

$$\mathbf{F}\iota = \underbrace{\begin{bmatrix} \mathbf{f}_{11} \\ \mathbf{f}_{21} \end{bmatrix} + \begin{bmatrix} \mathbf{f}_{12} \\ \mathbf{f}_{22} \end{bmatrix}}_{\text{consumption location}} = \underbrace{\begin{bmatrix} \mathbf{f}_{11} + \mathbf{f}_{12} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ \mathbf{f}_{21} + \mathbf{f}_{22} \end{bmatrix}}_{\text{production location}}. \tag{4.}$$

2.2.1.1. Value-added exports. Johnson & Noguera (2012a,b; 2018) decompose final goods by location of consumption.[3] The amount of value added from all countries required to produce final goods consumed by country j is

$$\begin{bmatrix} \mathbf{va}_{1j} \\ \mathbf{va}_{2j} \end{bmatrix} = \hat{\mathbf{v}}\hat{\mathbf{y}}^{-1}\,[\mathbf{I} - \mathbf{A}]^{-1}\begin{bmatrix} \mathbf{f}_{1j} \\ \mathbf{f}_{2j} \end{bmatrix}, \tag{5.}$$

[3]The reader is referred to Daudin et al. (2011) for related, early work on value-added exports and vertical trade.

where $\mathbf{va}_{ij}$ is the vector of industry-level value added from country i absorbed in country j.[4] I refer to the resulting value-added flows ($\mathbf{va}_{ij}$) as value-added exports because they track value added from the country in which it is produced to the destinations in which it is consumed, analogous to how gross exports track gross output from where it is produced to where it is sold. As a matter of accounting, adding up value-added exports across all destinations yields total value added: $\mathbf{va}_i = \sum_j \mathbf{va}_{ij}$.

This description of the geography of production versus consumption of value added is useful in various contexts. For example, canonical trade models are often written in value-added terms, abstracting from the production of and trade in intermediate inputs. Value-added exports measure trade flows in a manner consistent with this modeling approach.

Comparisons between value-added and gross exports can also shed light on the role that GVCs play in shaping gross trade flows. At the global level, the ratio of value-added to gross exports is inversely related to the number of borders crossed during the production process (Fally 2012). Thus, declines in this global ratio are evidence of the increasing cross-border fragmentation of production.

At the industry or bilateral level, gaps between gross and value-added trade flows hint at complex features of value chains. While value-added exports are always smaller than gross exports at the world or country level, this is not true for individual industries or bilateral country pairs. Value-added exports may exceed gross exports at the industry level because a given industry can export value added, as embodied both in its own exports and in the exports of downstream industries (e.g., computer chips are exported directly and embodied in exported computers). At the bilateral level, a country may sell value added to a given destination both directly (embodied in its own exports) and indirectly (embodied in downstream, third-country final or intermediate goods), as when Japan can sell value added, embodied in Chinese exports, to the United States.

2.2.1.2. Global value chain income. Timmer et al. (2013, 2014) and Los et al. (2015) use the decomposition of final goods by location of production to measure trade in value added on the production side. Without loss of generality, let us focus on decomposing the value added embodied in country 1's final goods production, which is given by

$$\begin{bmatrix} \mathbf{gvc}_{11} \\ \mathbf{gvc}_{21} \end{bmatrix} = \hat{\mathbf{v}}\hat{\mathbf{y}}^{-1}\left[\mathbf{I}-\mathbf{A}\right]^{-1} \begin{bmatrix} \mathbf{f}_{11}+\mathbf{f}_{12} \\ 0 \end{bmatrix}, \qquad 6.$$

where $\mathbf{gvc}_{ij}$ is the industry-level vector of value added from country i embodied in final goods produced by country j. This decomposition allocates the value added embodied in final goods to the source countries along the GVC that supply it. Put differently, it traces income generated in the production of final goods back to the countries in which that income is generated. Drawing on the language of Timmer et al. (2013), I thus refer to it as a decomposition of GVC income.[5]

This GVC income decomposition measures the domestic and foreign content of domestically produced final goods. As such, it is conceptually linked to existing work on offshoring (Feenstra & Hanson 1996, 1999) and task trade (Grossman & Rossi-Hansberg 2007, 2008). In this literature,

[4]Equivalently, we can write $\mathbf{va}_{ij} = \hat{\mathbf{v}}_i\hat{\mathbf{y}}_i^{-1}\mathbf{L}_{i1}\mathbf{f}_{1j} + \hat{\mathbf{v}}_i\hat{\mathbf{y}}_i^{-1}\mathbf{L}_{i2}\mathbf{f}_{2j}$, where $\mathbf{L}_{ik}$ represents block elements of $[\mathbf{I}-\mathbf{A}]^{-1}$ such that $\mathbf{L}_{ik}\mathbf{f}_{kj}$ is the amount of gross output from i needed to produce $\mathbf{f}_{kj}$. This representation emphasizes that value added from country i is sold to country j, as embodied both in final goods shipped from i to j ($\mathbf{f}_{ij}$) and in final goods that country j buys from itself ($\mathbf{f}_{jj}$).

[5]To be clear, the nationality of income in this decomposition is defined by the location in which value is added, not by the national ownership of the factors. Equation 6 measures total income, but income can be decomposed into payments to different factors of production, such as high- versus low-skilled labor, using auxiliary data (for an example, see Timmer et al. 2014).

the share of imported inputs in production has been used to measure the intensity of offshoring. GVC income improves on this measurement approach in two ways. First, GVC income takes into account the possibility that imported inputs include domestic content. Second, GVC income also captures the multilateral nature of GVCs better than direct import measures in that it measures bilateral foreign content in a way that allows for content to travel indirect routes (via third countries) from its source to where it is ultimately used in production.

To make both of these ideas concrete, consider trying to measure Mexican content in US-produced cars, and suppose that the United States uses imported engines from Mexico. The standard approach would be to treat the share of imported engines from Mexico in the value of US cars as a measure of offshoring to Mexico. The GVC income approach deals with two potentially important real-world complications. First, the United States might export inputs (e.g., spark plugs) to Mexico that are embodied in Mexican engines. Second, Mexican engines might include value-added content from third countries (e.g., steel from China). These higher-order input linkages would lead the conventional import share measure to overstate how much Mexican value added is embodied in US cars. By accounting for them, the GVC income approach would yield a more accurate breakdown of domestic versus foreign content in US cars and a more nuanced bilateral decomposition of foreign content across ultimate source countries.

2.2.2. Value-added content in gross exports. Value-added exports and GVC income are both defined by decomposing value-added content embodied in final goods; however, there is a large and active line of work that focuses instead on decomposing national content in gross exports.[6] Hummels et al. (2001) and the National Research Council (Nat. Res. Counc. 2006) use input–output tables to separate the domestic content from the import content of exports.[7] Because these early contributions use data for one country at a time, rather than a complete global input–output system, they are largely silent about the exact relationship between the domestic and foreign content of exports and the nationality of value-added content embodied in exports. Recent work by Johnson & Noguera (2012a), Koopman et al. (2014), and Los et al. (2016) has addressed these issues without resolving them fully. My objective in this section is to bring additional clarity to this issue.

To start, I reorganize Equation 1 to isolate exports for country 1:

$$\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{A}_{11} & 0 \\ \mathbf{A}_{21} & \mathbf{A}_{22} \end{bmatrix}}_{\equiv \mathbf{A}^*} \begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix} + \underbrace{\begin{bmatrix} \mathbf{f}_{11} & 0 \\ \mathbf{f}_{21} & \mathbf{f}_{22} \end{bmatrix}}_{\equiv \mathbf{F}^*} \iota + \begin{bmatrix} \mathbf{x}_{12} \\ 0 \end{bmatrix} \quad \text{with} \quad \mathbf{x}_{12} = \mathbf{A}_{12}\mathbf{y}_2 + \mathbf{f}_{12}. \qquad 7.$$

This reorganization removes input shipments from country 1 to country 2 ($\mathbf{A}_{12}\mathbf{y}_2$) from the global input–output matrix ($\mathbf{A}$) and deposits them in exports ($\mathbf{x}_{12}$), thus leaving us with modified input–output matrix $\mathbf{A}^*$.

[6]Although this particular decomposition has attracted much attention in policy circles and the extant literature, the theoretical motivation for decomposing gross exports is not entirely clear. While domestic value added in exports (defined below) can be thought of as the amount by which domestic value added would rise if home exports exogenously increase, foreign value added in exports (again, defined below) does not have the same interpretation. The reason for this is that the foreign value added–to-output ratio depends on the level of home exports (foreign imports); in contrast, the domestic value added–to-output ratio can be held constant as home exports increase. This implies that one cannot straightforwardly apply counterfactual arguments to interpret the meaning of foreign value added in exports. The interpretation I provide for domestic or foreign value-added content in exports sidesteps these issues by avoiding counterfactual arguments in justifying the export decomposition. That is, the decomposition in this review is a manipulation of accounting identities that hold in a given equilibrium.

[7]Chenery et al. (1986) use input–output tables to measure the import content of exports, as well, as part of an analysis of structural transformation in developing countries.

As in the sections above, I manipulate Equation 7 to compute the gross output required to produce $\mathbf{x}_{12}$ and then premultiply by the value added–to-output ratios to compute the value-added content embodied in country 1's exports:

$$\begin{bmatrix} \mathbf{xc}_{11} \\ \mathbf{xc}_{21} \end{bmatrix} = \hat{\mathbf{v}}\hat{\mathbf{y}}^{-1}\left[\mathbf{I} - \mathbf{A}^*\right]^{-1} \begin{bmatrix} \mathbf{x}_{12} \\ 0 \end{bmatrix} = \begin{bmatrix} \hat{\mathbf{v}}_1\hat{\mathbf{y}}_1^{-1}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12} \\ \hat{\mathbf{v}}_2\hat{\mathbf{y}}_2^{-1}[\mathbf{I} - \mathbf{A}_{22}]^{-1}\mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12} \end{bmatrix}, \qquad 8.$$

where $\mathbf{xc}_{ij}$ is the industry-level vector of value added from country i required to produce exports of country j. Adding up across industries, the total amount of domestic value added embodied in country 1's exports is $\boldsymbol{\iota}'\mathbf{xc}_{11}$, and the total foreign value added in country 1's exports is $\boldsymbol{\iota}'\mathbf{xc}_{21}$.

Although I have used a global input–output framework to define domestic value added in exports in this section, the resulting formula (somewhat surprisingly) predates the advent of global input–output analysis. Hummels et al. (2001) define the import content of exports—equivalently, the vertical specialization trade—as $\mathbf{VS} \equiv \boldsymbol{\iota}'\mathbf{A}_{21}(\mathbf{I} - \mathbf{A}_{11})^{-1}\mathbf{x}_{12}$. The complement to the import content of exports is then the domestic content of exports, which equals exports less the import content of exports (Nat. Res. Counc. 2006). It is straightforward to prove that the domestic content of exports is equivalent to domestic value added in exports:

$$\mathbf{DC} \equiv \boldsymbol{\iota}'\mathbf{x}_{12} - \mathbf{VS} = \boldsymbol{\iota}'[\mathbf{I} - \mathbf{A}_{11} - \mathbf{A}_{21}](\mathbf{I} - \mathbf{A}_{11})^{-1}\mathbf{x}_{12} = \boldsymbol{\iota}'\hat{\mathbf{v}}_1\hat{\mathbf{y}}_1^{-1}(\mathbf{I} - \mathbf{A}_{11})^{-1}\mathbf{x}_{12} = \boldsymbol{\iota}'\mathbf{xc}_{11}. \qquad 9.$$

Thus, the literature has long been measuring domestic value added in exports without explicitly stating it. Applying the hypothetical extraction method from the input–output literature to define domestic value added in exports, Los et al. (2016) reach the same conclusion.[8]

The new aspect of the value-added analysis in Equation 8 is the definition of foreign value added in exports. To interpret the elements of $\mathbf{xc}_{21}$, note that $[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}$ is the vector of country 1's output needed to produce its exports, which means that $\mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}$ is the vector of imported intermediate inputs used in production of exports. In turn, $[\mathbf{I} - \mathbf{A}_{22}]^{-1}\mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}$ is the vector of foreign output needed to produce those inputs imported by country 1, so multiplying that output by $\hat{\mathbf{v}}_2\hat{\mathbf{y}}_2^{-1}$ returns the country 2 value added required to produce country 1's exports.

An important point to note is that the amount of country 2 value added needed to produce country 1's exports ($\boldsymbol{\iota}'\mathbf{xc}_{21}$) is not equal to the import content of exports. In particular, the import content of exports can be decomposed into two terms:

$$\begin{aligned} \mathbf{VS} &= \boldsymbol{\iota}'\mathbf{xc}_{21} + \left[\mathbf{VS} - \boldsymbol{\iota}'\mathbf{xc}_{21}\right] && 10. \\ &= \boldsymbol{\iota}'\mathbf{xc}_{21} + \left[\boldsymbol{\iota}'\mathbf{A}_{21}(\mathbf{I} - \mathbf{A}_{11})^{-1}\mathbf{x}_{12} - \boldsymbol{\iota}'\hat{\mathbf{v}}_2\hat{\mathbf{y}}_2^{-1}[\mathbf{I} - \mathbf{A}_{22}]^{-1}\mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}\right] && 11. \\ &= \boldsymbol{\iota}'\mathbf{xc}_{21} + \boldsymbol{\iota}'\mathbf{A}_{12}[\mathbf{I} - \mathbf{A}_{22}]^{-1}\mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}. && 12. \end{aligned}$$

The first term is just foreign value added in exports. The second term is a double-counting residual equal to the value of inputs imported by country 2 that are used to produce country 2 inputs that are embodied in country 1's exports.[9]

[8]Los et al. (2016) define domestic value added in exports as true home GDP less what home GDP would be in a counterfactual world in which $\mathbf{x}_{12}$ is removed (extracted) from the input–output system. This is essentially equivalent to the operation in Equation 8, which does not actually involve any counterfactual calculations. However, whereas Equation 8 includes both domestic and foreign value-added content, Los et al. (2016) compute domestic value added in exports only by zeroing out the ratio of value added to gross output for country 2 (equivalent to setting $\mathbf{v}_2 = 0$).

[9]To interpret this residual, recall that $[\mathbf{I} - \mathbf{A}_{22}]^{-1}\mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}$ is the gross output from country 2 that is needed to produce country 1's exports. Premultiplying this output by $\mathbf{A}_{12}$ yields the value of exported inputs from country 1 that are themselves used to produce country 1's exports. These inputs are ultimately used up in the production process, and thus are not associated with value added that is attributable to any any source country. I discuss this interpretation further in Section 5.

To sum up this discussion, gross exports can be decomposed into value-added content as follows:

$$\iota'\mathbf{x}_{12} = \overbrace{\iota'\mathbf{x}\mathbf{c}_{11}}^{\text{domestic VA}} + \underbrace{\overbrace{\iota'\mathbf{x}\mathbf{c}_{21}}^{\text{foreign VA}} + \underbrace{\iota'\mathbf{A}_{12}[\mathbf{I}-\mathbf{A}_{22}]^{-1}\mathbf{A}_{21}[\mathbf{I}-\mathbf{A}_{11}]^{-1}\mathbf{x}_{12}}_{\text{double-counting residual}}}_{\text{import content of exports}}. \quad 13.$$

This decomposition splits exports into domestic value-added content and import content and then decomposes import content into foreign value-added content and a double-counting residual resulting from round-trip trade in inputs.[10] Although this is obvious in Equation 13, I point out that gross exports exceed the total underlying value-added content embodied in them: $\iota'\mathbf{x}_{12} \geq \iota'\mathbf{x}\mathbf{c}_{11} + \iota'\mathbf{x}\mathbf{c}_{21}$.[11]

I make two brief remarks about this decomposition. First, while I have focused on a two-country case in this section, this approach to measuring value-added content in exports can be applied to bilateral trade as well. Using the many-country analog to Equation 7, one can compute the value-added content embodied in any bilateral export flow ($\mathbf{x}_{ij}$). One complication is that bilateral export decompositions of this sort are not additive: If one computes the amount of value added from country i in $\mathbf{x}_{ij}$ and then computes the amount of value added from country i in $\mathbf{x}_{ik}$, one cannot simply add these together to obtain the amount of value added from country i embodied in the total flow $\mathbf{x}_{ij} + \mathbf{x}_{ik}$. The reason for this is that the appropriate $\mathbf{A}^*$ matrix depends on the export flow being decomposed and is thus different depending on whether we decompose $\mathbf{x}_{ij}$ and $\mathbf{x}_{ik}$ independently or decompose the composite flow $\mathbf{x}_{ij} + \mathbf{x}_{ik}$. Thus, care is needed to do the decomposition that is most sensible for the question at hand.

Second, the export decomposition in Equation 13 is different than the export decomposition proposed by Koopman et al. (2014). The origin of the difference is deceptively simple. In Equation 8, I multiply exports by $[\mathbf{I}-\mathbf{A}^*]^{-1}$ to compute output required to produce exports, consistent with the work of Los et al. (2016). In contrast, Koopman et al. multiply exports by $[\mathbf{I}-\mathbf{A}]^{-1}$. Interpreted as an attempt to compute output required to produce exports, the Koopman et al. approach treats input shipments $\mathbf{A}_{12}\mathbf{y}_2$ in two inconsistent ways: It includes them in both exports and the input requirements matrix simultaneously. By including $\mathbf{A}_{12}\mathbf{y}_2$ in exports only, we uncouple the input–output system: Given $\mathbf{x}_{12}$, $\mathbf{y}_1$ does not depend on $\mathbf{y}_2$ directly. This implies that one can work backward from gross exports to gross output and from gross output to value added, thus decomposing exports into value-added components in an economically meaningful way. I discuss these mechanics further in Section 5.

2.2.3. Measuring factor and environmental content. The same input–output techniques used above to measure value-added content can be readily adapted to measure trade in factor and environmental content. To see this, note that the matrix $\hat{\mathbf{v}}\hat{\mathbf{y}}^{-1}$ in Equations 5, 6, and 8 contains

[10]This decomposition can be pushed further. For example, following Johnson & Noguera (2012a) and Los et al. (2016), the domestic value-added content of exports can be split into value-added exports (domestic value added consumed abroad) and reimports of domestic value added (domestic value-added content in exports that is ultimately consumed at home, embodied in reimported foreign goods). Furthermore, one can distinguish between value-added content embodied in final goods and that embodied in intermediate goods, as pursued by Koopman et al. (2014) and Los et al. (2016). The exact decomposition one would want to use needs to be guided by the question that requires an answer.

[11]This expression holds with equality when exports from country 1 consist entirely of final goods, so that $\mathbf{x}_{12} = \mathbf{f}_{12}$ and $\mathbf{A}_{12} = 0$. One way to understand this is that we have $\mathbf{A} = \mathbf{A}^*$ in this special case. Another is that the value of final goods is equal to the underlying value-added content embodied in them.

value added–to-output ratios—i.e., the value of payments to primary factors per dollar (or any other currency unit) of output. In place of these value added–to-output ratios, one could substitute the ratio of factor quantities required to produce a dollar of output to measure trade in factors, or environmental quantities (e.g., pollution or carbon emissions) per unit of output to measure environmental trade.

As above, one can measure trade in terms of the location in which factors are used in production versus where they are consumed (like value-added exports), measure the factor content of final goods produced in a given destination (like GVC income), or measure the quantities of factors required to produce exports (like export content). Reimer (2006), Trefler & Zhu (2010), and Puzzello (2012) focus on measuring net factor trade, which amounts to computing domestic factors required to produce value-added exports less foreign factors required to produce value-added imports (equivalently, factors embodied in a country's production versus in its consumption). Similarly, in the environmental literature, there is a debate about whether countries ought to commit to carbon emissions targets or carbon consumption targets, which would require measuring the carbon content of final goods. In a related vein, Grether & Mathys (2013) use a global input–output framework to compute the pollution terms of trade.

2.3. Measuring Location in and Length of Value Chains

Input–output tables have also recently been put to use to describe the length of the value chain and the location (upstream versus downstream) of individual industries or countries in it. Following the literature, I focus on explaining the essential ideas in a closed economy, which can then be generalized to a many-country setting.

To do so, I aggregate the global input–output framework across countries:

$$\bar{\mathbf{y}} = \bar{\mathbf{A}}\bar{\mathbf{y}} + \bar{\mathbf{f}} \tag{14.}$$

and

$$\bar{\mathbf{y}} = \bar{\mathbf{v}}' + \iota'\bar{\mathbf{A}}\hat{\bar{\mathbf{y}}} = \bar{\mathbf{v}}' + \bar{\mathbf{y}}'\bar{\mathbf{B}}, \tag{15.}$$

where $\bar{\mathbf{y}} = \sum_i \mathbf{y}_i$ and $\bar{\mathbf{f}} = \sum_i \sum_j \mathbf{f}_{ij}$ are (respectively) gross output and final expenditure for the world, $\bar{\mathbf{A}} = \left[\sum_i \sum_j \mathbf{A}_{ij}\hat{\mathbf{y}}_j\right]\hat{\bar{\mathbf{y}}}^{-1}$ is the industry-to-industry input–output matrix for the world, and $\bar{\mathbf{B}} = \hat{\bar{\mathbf{y}}}^{-1}\bar{\mathbf{A}}\hat{\bar{\mathbf{y}}}$ is a matrix that records the share of output from industry i used by downstream industry j. Equations 14 and 15 can be rewritten as:

$$\bar{\mathbf{y}} = \left[\mathbf{I} - \bar{\mathbf{A}}\right]^{-1}\bar{\mathbf{f}} = \left(\mathbf{I} + \bar{\mathbf{A}} + \bar{\mathbf{A}}^2 + \bar{\mathbf{A}}^3 + \cdots\right)\bar{\mathbf{f}} \tag{16.}$$

and

$$\bar{\mathbf{y}}' = \bar{\mathbf{v}}'\left[\mathbf{I} - \bar{\mathbf{B}}\right]^{-1} = \bar{\mathbf{v}}'\left(\mathbf{I} + \bar{\mathbf{B}} + \bar{\mathbf{B}}^2 + \bar{\mathbf{B}}^3 + \cdots\right). \tag{17.}$$

The second equality in these equations replaces $\left[\mathbf{I} - \bar{\mathbf{A}}\right]^{-1}$ (the Leontief Inverse) or $\left[\mathbf{I} - \bar{\mathbf{B}}\right]^{-1}$ (the Ghosh Inverse) with their geometric series expansions, effectively opening up the production process to track value chain linkages one stage at a time.

To interpret Equation 16, output can be decomposed into final goods plus the value of intermediate inputs used up in the production process, where $\bar{\mathbf{A}}\bar{\mathbf{f}}$ are inputs directly used to produce final goods, $\bar{\mathbf{A}}^2\bar{\mathbf{f}}$ are the inputs used to produce the inputs, and so on. Equation 17 has a similar interpretation: The value of output can be decomposed into direct value added in the sector from which output originates plus value added from other sectors embodied in inputs sourced further up the value chain, where $\bar{\mathbf{v}}'\bar{\mathbf{B}}$ is value added contributed one step back in the chain (direct value added in inputs), $\bar{\mathbf{v}}'\bar{\mathbf{B}}^2$ is value added from two steps back in the chain (direct value added in the inputs of those inputs), and so on.

Measures of both length and position can be motivated with reference to these standard input–output results. The core idea in both is that we can use the stage-by-stage descriptions of the production process to count production stages—the number of stages that industry output transits through prior to reaching final demand (using Equation 16) or the number of stages required to produce an industry's output (using Equation 17). This counting idea has recently been introduced into the international economics literature by Fally (2012) and Antràs & Chor (2013), and it was previously used in the input–output literature by Dietzenbacher et al. (2005) and Dietzenbacher & Romero (2007) to characterize distance between industries (termed average propagation lengths).

In the case of value chain position, Fally (2012) and Antràs & Chor (2013) define an index of whether industries are located upstream versus downstream in the value chain.[12] Intuitively, industries will be more downstream—i.e., close to final demand—when they produce final goods or inputs that are directly used to produce those final goods. Alternatively, industries will be more upstream when they produce inputs that are used to produce inputs (or higher-order inputs).

Building on these ideas, let us say that final goods are one step away from demand, inputs directly used to produce final goods are two steps away from demand, inputs used to produce inputs are three steps away from demand, and so on. Furthermore, let us weight the count by the share of the value of output at each production stage in total output. This yields the following index of industry upstreamness:

$$\mathbf{U} = 1\hat{\bar{\mathbf{y}}}^{-1}\bar{\mathbf{f}} + 2\hat{\bar{\mathbf{y}}}^{-1}\bar{\mathbf{A}}\bar{\mathbf{f}} + 3\hat{\bar{\mathbf{y}}}^{-1}\bar{\mathbf{A}}^2\bar{\mathbf{f}} + 4\hat{\bar{\mathbf{y}}}^{-1}\bar{\mathbf{A}}^3\bar{\mathbf{f}} + \cdots = \hat{\bar{\mathbf{y}}}^{-1}\left[\mathbf{I} - \bar{\mathbf{A}}\right]^{-2}\bar{\mathbf{f}}. \qquad 18.$$

This index is a value-weighted count of the number of stages that output of an industry passes through prior to reaching final consumers, so larger values of the index indicate that an industry is further upstream.

One nice feature of this upstreamness index is that it has an intuitive link to standard results in input–output analysis. Specifically, the upstreamness index can be rewritten as

$$\mathbf{U} = \hat{\bar{\mathbf{y}}}^{-1}\left[\mathbf{I} - \bar{\mathbf{A}}\right]^{-2}\bar{\mathbf{f}} = \hat{\bar{\mathbf{y}}}^{-1}\left[\mathbf{I} - \bar{\mathbf{A}}\right]^{-1}\hat{\bar{\mathbf{y}}}\iota = \left[\mathbf{I} - \bar{\mathbf{B}}\right]^{-1}\iota. \qquad 19.$$

The upstreamness index is thus the row sum of the Ghosh Inverse matrix, which is a standard measure of the strength of total forward linkages in the production process. That is, upstream industries have stronger forward linkages.

In a complementary vein, Fally (2012) develops a measure of production chain length. While Fally develops this length index using a recursive argument, I present a counting stages argument using Equation 17 in this section, paralleling the argument used above to define the upstreamness index.[13]

Suppose that we count production stages backward for production of a given good, where direct value added is stage 1, direct value added in inputs is stage 2, direct value added in inputs

[12] Although Fally (2012) and Antràs & Chor (2013) use different arguments to develop their upstreamness indexes, Antràs et al. (2012) emphasize that the resulting indexes are equivalent. My discussion in this section follows Antràs & Chor (2013).

[13] Starting from the observation that the number of stages embodied in a good is equal to one (the stage via which the good itself is produced) plus the number of stages embodied in that good's intermediate inputs, Fally (2012) defines value chain length recursively as $\mathbf{N} = \iota + \bar{\mathbf{A}}'\mathbf{N}$, so that $\mathbf{N} = \left[\mathbf{I} - \bar{\mathbf{A}}'\right]^{-1}\iota$, which is evidently the transpose of Equation 20. Miller & Temurshoev (2017) treat $\mathbf{N}'$ as a measure of input downstreamness, which measures the distance of a given industry from primary factors of production (i.e., value added).

to inputs is stage 3, and so on. Let us again weight this count using input use at each stage as a share of total output. This argument yields the following weighted-count of the number of stages embodied in industry-level output:

$$\mathbf{N}' = 1\bar{\mathbf{v}}'\hat{\bar{\mathbf{y}}}^{-1} + 2\bar{\mathbf{v}}'\bar{\mathbf{B}}\hat{\bar{\mathbf{y}}}^{-1} + 3\bar{\mathbf{v}}'\bar{\mathbf{B}}^2\hat{\bar{\mathbf{y}}}^{-1} + 4\bar{\mathbf{v}}'\bar{\mathbf{B}}^3\hat{\bar{\mathbf{y}}}^{-1} + \cdots \qquad 20.$$

$$= \bar{\mathbf{v}}'\left[\mathbf{I} - \bar{\mathbf{B}}\right]^{-2}\hat{\bar{\mathbf{y}}}^{-1} \qquad 21.$$

$$= \boldsymbol{\iota}'\left[\mathbf{I} - \bar{\mathbf{A}}\right]^{-1}, \qquad 22.$$

where the third line follows by recognizing that $\boldsymbol{\iota}'\hat{\bar{\mathbf{y}}} = \bar{\mathbf{v}}'\left[\mathbf{I} - \bar{\mathbf{B}}\right]^{-1}$ and $\hat{\bar{\mathbf{y}}}\left[\mathbf{I} - \bar{\mathbf{B}}\right]^{-1}\hat{\bar{\mathbf{y}}}^{-1} = \left[\mathbf{I} - \bar{\mathbf{A}}\right]^{-1}$ (Miller & Blair 2009, chapter 12).

Again, the length index has a clean input–output interpretation: The length of an industry's value chain is equal to the column sum of the Leontief Inverse. In the input–output literature, column sums of the Leontief Inverse are a commonly used measure of total backward linkages [the change in total gross output ($\boldsymbol{\iota}'\bar{\mathbf{y}}$) resulting from a change in final demand in a particular industry]. Thus, length in this case is capturing the idea that downstream stimulus generates more intermediate demand, and thus total output, when value chains are longer.

While I have defined position and length at the industry level (for a closed world economy), these measures can be extended to the global input–output framework. For example, Fally & Hillberry (2015) quantify the location of individual countries (or country–sector pairs) in Asian value chains, using many-country (regional) input–output tables for Asia. Furthermore, while the length and upstreamness measures above are computed for industries, it is also possible to measure the relative location and/or distance between industry pairs using similar weighted-count arguments. Specifically, Dietzenbacher et al. (2005) and Dietzenbacher & Romero (2007) compute the average number of stages it takes for a demand change (or value-added cost change) in sector i to propagate to gross output in sector j (termed the average propagation length), which Alfaro et al. (2015) use to test a model of firm boundaries.

2.4. Price Linkages and Trade Cost Aggregation

By linking production processes together across borders, GVCs give rise to price spillovers—changes in unit costs or trade frictions upstream spill over to influence the prices of downstream producers. In this section, I illustrate how input–output techniques can be applied to study these price linkages.

As a reference point, let us start by examining price linkages in a stylized, multi-country model of roundabout production. For simplicity, suppose that each country produces a single composite good, that output is produced by combining intermediates with primary factors (e.g., labor) under competitive conditions, and that output from each country is used as both a final and an intermediate good. Furthermore, let the production function be Cobb-Douglas, so output from country i is $q_i = A_i l_i^{1-\alpha_i}\prod_j z_{ji}^{\alpha_{ji}}$, with $\sum_j \alpha_{ji} = \alpha_i$.

The price of gross output in country i is then a function of factor costs and input prices: $p_i = \left[p_i^v/(1-\alpha_i)\right]^{1-\alpha_i}\prod_j \left(p_{ji}/\alpha_{ji}\right)^{\alpha_{ji}}$, where $p_i^v = w_i/A_i^{1/(1-\alpha_i)}$ is the price of real value added originating from country i, and $p_{ji} = \tau_{ji}p_j$ is the delivered cost of intermediates from country j, and with $\tau_{ji} = 1 + t_{ji}$, where t_{ji} denotes ad valorem trade costs. Log changes in prices are given by

$$\Delta \ln \mathbf{p} = \left[\mathbf{I} - \mathbf{A}'\right]^{-1}\left[\mathbf{I} - \hat{\alpha}\right]\Delta \ln \mathbf{p}^v + \left[\mathbf{I} - \mathbf{A}'\right]^{-1}\left[\mathbf{A}' \circ \Delta \ln \mathbf{T}'\right]\boldsymbol{\iota}, \qquad 23.$$

where $\mathbf{p}$ and $\mathbf{p}^v$ are $(N \times 1)$-dimensional price vectors, $\mathbf{A}$ is a $(N \times N)$-dimensional input–output matrix with elements α_{ij}, $\hat{\alpha}$ is a $(N \times N)$-dimensional matrix with α_is along the diagonal, and $\mathbf{T}$ is a $(N \times N)$-dimensional matrix with elements τ_{ij}.[14]

The first term in Equation 23 captures the role of input linkages in transmitting cost push shocks across countries. The price of gross output from country i is a function of value-added prices (costs) in all countries, where the weight that country i puts on country j's value-added price depends on input linkages via the matrix $[\mathbf{I} - \mathbf{A}']^{-1}$. The direct effect of a 1% cost shock in country j is to raise country j's own gross-output price [by $(1 - \alpha_j)$%], and the rise in the price in country j's gross output is transmitted forward to countries that use country j's inputs in production either directly or indirectly embedded in inputs to their inputs. Thus, it is helpful to think of $[\mathbf{I} - \hat{\alpha}]\, \Delta \ln \mathbf{p}^v$ as capturing the direct component of cost push shocks, while $[\mathbf{I} - \mathbf{A}']^{-1} [\mathbf{I} - \hat{\alpha}]\, \Delta \ln \mathbf{p}^v$ is the total effect. In macro applications, Auer et al. (2017) use this relationship to study the propagation of cost shocks and synchronization of producer price inflation across countries, while Bems & Johnson (2017) exploit it in defining value-added real effective exchange rates.

The second term captures how the same cost push mechanism governs the impact of upstream trade costs on downstream output prices. The direct effect of changes in trade costs is given by $\left[\mathbf{A}' \circ \Delta \ln \mathbf{T}'\right] \boldsymbol{\iota}$, a weighted average of changes in trade costs, with weights that depend on the importance of individual inputs in production. These direct effects then trigger indirect effects as they are passed downstream, again captured by the $[\mathbf{I} - \mathbf{A}']^{-1}$ matrix. The total impact of changes in trade costs on gross output prices combines these direct and indirect effects.

If we step back from this model-based discussion, we can see that there is a direct link between these results and standard cost push analysis in the input–output literature and extensions thereof that have been used to compute accumulated trade costs along the GVC. To explain this, I must digress on the definition of value added. In the input–output literature (as in Section 2.1), value added is typically defined as the difference between the value of output and the value of inputs used, both evaluated at basic prices (the price that sellers receive).[15] This is an abuse of language: Value added in the national (production) accounts is defined as output at basic prices less the value of inputs used at the purchaser's prices, as in $\widetilde{\mathbf{v}}' = \mathbf{y}' - \boldsymbol{\iota}'\tilde{\mathbf{Z}}$, with $\tilde{\mathbf{Z}}$ denoting the value of inputs at the purchaser's prices. Recognizing this, I rewrite Equation 2 as

$$\mathbf{v}' = \mathbf{y}' - \boldsymbol{\iota}'\mathbf{Z} = \widetilde{\mathbf{v}}' + \boldsymbol{\iota}'\mathbf{M}, \qquad 24.$$

where $\mathbf{M} = \tilde{\mathbf{Z}} - \mathbf{Z}$ is the gap between the values of inputs at the purchaser's prices and at basic prices. Typically referred to as the margin in input–output analysis, $\mathbf{M}$ is composed of transport margins, border tariffs or subsidies, and other taxes or subsidies on input use.

Substituting Equation 24 into Equation 15, we can decompose the value of output as follows:

$$\mathbf{y}' = \widetilde{\mathbf{v}}' [\mathbf{I} - \mathbf{B}]^{-1} + \boldsymbol{\iota}'\mathbf{M} [\mathbf{I} - \mathbf{B}]^{-1} = \widetilde{\mathbf{v}}'\hat{\mathbf{y}}^{-1} [\mathbf{I} - \mathbf{A}]^{-1} \hat{\mathbf{y}} + \boldsymbol{\iota}'\mathbf{M}\hat{\mathbf{y}}^{-1} [\mathbf{I} - \mathbf{A}]^{-1} \hat{\mathbf{y}}, \qquad 25.$$

[14]The log price change for output from country i is $\Delta \ln p_i = (1 - \alpha_i)\Delta \ln p_i^v + \sum_j \alpha_{ji} \left[\Delta \ln \tau_{ji} + \Delta \ln p_j\right]$, where $\Delta \ln p_i^v = \Delta \ln w_i - (1/1 - \alpha_i)\Delta \ln A_i$. Equation 23 follows from stacking and manipulating these country-level equations. By way of notation, $\circ$ denotes the Hadamard (element-wise) product of matrices. Furthermore, while I focus on log price changes in this section (as in typical macro applications), these same arguments obviously hold for log prices and for log-linearizations of more general price indexes (e.g., nested constant elasticity of substitution). One final note is that, when trade costs are positive, the matrix $\mathbf{A}$ here is not quite the input-output matrix published by statistical authorities—whereas published input-output data are reported in basic prices, expenditure shares α_{ji} here ought to be measured in purchaser's prices. I will not belabor this issue, as it is not central to the story.

[15]Miller & Blair (2009, chapter 1) provide examples. Assuming that $\mathbf{y}$ and $\mathbf{Z}$ are both measured at basic prices, as in typical input–output tables, Equation 2 matches this definition. In defense of this approach, this definition is close to GDP, since GDP (final demand at purchasers purchaser's prices) equals value added plus net taxes. Thus, $\boldsymbol{\iota}'\mathbf{v}$ equals GDP less the net margins that apply to final goods.

where the second equality follows from the relationship between the Ghosh and Leontief Inverses. In this case, margins are a component of production costs, and they have both direct and indirect impacts on the value of output, just like any other production cost. The total share of those margins in the value of output is $\boldsymbol{\iota}'\mathbf{M}\left[\mathbf{I}-\mathbf{B}\right]^{-1}\hat{\mathbf{y}}^{-1}=\boldsymbol{\iota}'\mathbf{M}\hat{\mathbf{y}}^{-1}\left[\mathbf{I}-\mathbf{A}\right]^{-1}$.[16]

To illustrate how this result can be used for aggregating trade costs, suppose that $\mathbf{M}$ consists entirely of tariffs. Thus, the vector $\mathbf{t}$ records the share of trade costs in the value of output for all countries: $\mathbf{t}=\left[\mathbf{I}-\mathbf{A}'\right]^{-1}\mathbf{y}^{-1}\mathbf{M}'\boldsymbol{\iota}=\left[\mathbf{I}-\mathbf{A}'\right]^{-1}\left[\mathbf{A}'\circ\mathbf{T}'\right]\boldsymbol{\iota}$, where $\mathbf{T}$ is a matrix of tariff rates.[17] This has obvious parallels to how trade costs are aggregated in Equation 23, wherein upstream tariffs have both direct and indirect effects on costs for downstream producers.

Taking this one step further, Miroudot et al. (2013) define the cumulative tariff as the direct tariff that j puts on i plus the accumulated burden of upstream tariffs:

$$\mathbf{cumtariff}=\mathbf{T}+\left[\mathbf{I}-\mathbf{A}'\right]^{-1}\left[\mathbf{A}'\circ\mathbf{T}'\right]\boldsymbol{\iota}\boldsymbol{\iota}', \tag{26}$$

where the ij element of **cumtariff** is the cumulative tariff that j faces in importing from i. Put differently, it is the increase in the cost of country i's goods from country j's perspective that results from the entire structure of tariffs along the value chain.[18]

This cumulative tariff concept, along with the representation of price linkages in Equation 23, points to important uses of input–output logic to study shock propagation and the burden of trade costs. That said, existing work in this area likely only scratches the surface of what is possible. I briefly mention two potentially fruitful areas for work. First, while the cumulative tariff aggregates trade costs in terms of their impact on producer prices, one wonders how one might aggregate trade costs so as to cumulate the impact they have on demand, either for gross output or for value added produced by a given country. Second, a venerable literature on effective rates of protection considers how tariffs ought to be aggregated to measure total protection of domestic value added.[19] As in the work of Anderson (1998), one needs a model to properly compute effective protection, and thus, more work on how value chains influence the mapping from gross tariffs to effective protection in standard models would be useful. Both of these areas for further work require more attention to to be paid to combining data with models, so I turn in the next section to a discussion of recent work that does just that.

2.5. Input–Output Linkages in Trade and Macroeconomic Models

There are many positive and normative questions about GVCs that cannot be answered by data alone. Although the focus of this review is on measurement, I pause in this section to highlight work

[16]Starting from a Leontief price model, Muradov (2017) derives essentially the same result. I instead focus on decomposing the value of output directly. To link my formula to Muradov's exposition, note that $\boldsymbol{\iota}'\mathbf{M}\hat{\mathbf{y}}^{-1}$ collapses a row vector of the cumulative tax paid as a share of gross output, so the share of taxes in the value of gross output can be rewritten as $\mathbf{m}'\left[\mathbf{I}-\mathbf{A}\right]^{-1}$, where $\mathbf{m}'$ is a vector of margin ratios.

[17]The intermediate steps are $\left[\mathbf{I}-\mathbf{A}'\right]^{-1}\mathbf{y}^{-1}\mathbf{M}'\boldsymbol{\iota}=\left[\mathbf{I}-\mathbf{A}'\right]^{-1}\hat{\mathbf{y}}^{-1}\left[\mathbf{Z}'\circ(\mathbf{M}'\oslash\mathbf{Z}')\right]\boldsymbol{\iota}=\left[\mathbf{I}-\mathbf{A}'\right]^{-1}\left[\hat{\mathbf{y}}^{-1}\mathbf{Z}'\circ(\mathbf{M}'\oslash\mathbf{Z}')\right]\boldsymbol{\iota}=\left[\mathbf{I}-\mathbf{A}'\right]^{-1}\left[\mathbf{A}'\circ\mathbf{T}'\right]\boldsymbol{\iota}$. Generally, the total value of tax paid can be decomposed into the tax rate on inputs versus the total value of inputs: $\mathbf{M}=(\mathbf{M}\oslash\mathbf{Z})\circ\mathbf{Z}$, where $\oslash$ and $\circ$ indicate Hadamard (element-wise) division and multiplication, respectively, and $\mathbf{M}\oslash\mathbf{Z}$ is a matrix of tax rates on purchased inputs.

[18]In computing cumulative tariffs, one might take care to distinguish input and final goods tariffs, as in $\mathbf{CT}=\mathbf{T}_{output}+\left[\mathbf{I}-\mathbf{A}'\right]^{-1}\left[\mathbf{A}'\circ\mathbf{T}'_{input}\right]\boldsymbol{\iota}\boldsymbol{\iota}'$, where $\mathbf{T}_{output}$ is the tariff applied on output sold to downstream users (either input or final goods tariffs, depending on downstream use) and $\mathbf{T}_{input}$ are input tariffs. I set $\mathbf{T}_{output}=\mathbf{T}_{input}$ in the main text, suppressing this distinction. Miroudot et al. (2013) compute cumulative tariffs using final goods tariffs in place of $\mathbf{T}_{output}$.

[19]Diakantoni et al. (2017) extend the classic effective protection formula to use data on bilateral input linkages and tariffs. Because their formula is based on the classic literature, strong (arguably implausible) assumptions are needed to interpret it as measuring effective protection in general equilibrium.

that uses global input–output data to study the quantitative role of GVC linkages in international trade and macroeconomic models.

Input–output data have long been used to calibrate quantitative models of international trade. The Global Trade Analysis Project (GTAP) computable general equilibrium model, which includes a rich set of input–output linkages, has been a workhorse for trade policy researchers and policy makers for over 30 years. Recent years have seen renewed interest in computable general equilibrium models based on microfoundations that yield gravity equations for trade. Caliendo & Parro (2015) develop a quantitative Ricardian model with input–output linkages across industries (see also Eaton et al. 2016b, Levchenko & Zhang 2016), and Costinot & Rodríguez-Clare (2014) discuss the role of input–output linkages at length in their handbook article on quantitative trade models.

While these models all include both cross-industry and cross-country input–output linkages, they treat cross-country linkages in a stylized way: They assume that industry-level bilateral final and intermediate trade shares are identical and that the allocation of imported inputs across sectors is the same as the allocation of domestic inputs. This amounts to applying two proportionality assumptions, one at the border to split final goods and inputs and another behind the border to allocate inputs across industries. In practice, neither assumption holds in available input–output data sets. To match observed expenditure allocations exactly, one needs to introduce more flexibility—e.g., additional frictions or technology differences. Along these lines, Johnson & Noguera (2017) calibrate an Armington-style model to match expenditure patterns exactly in studying changes in value-added exports over time, as do Caliendo et al. (2017) in quantifying the GDP cost of distortions in consumption and input use.

Fally & Hillberry (2015), Johnson & Moxnes (2016), and Antràs & de Gortari (2017) all use global input–output data to calibrate and estimate models with sequential multistage production. One important feature of all of these models is that they seek to match differences in the pattern of final goods versus input shipments across countries via endogenous decisions about where to locate individual production stages given trade frictions. Furthermore, Fally & Hillberry (2015) provide a model-based analysis of production chain position, using the upstreamness measures discussed in Section 2.3.

In international macroeconomics, Johnson (2014) uses global input–output data to calibrate an international real business cycle model with input–output linkages to study the propagation of productivity shocks and the role of input trade in explaining the trade-comovement puzzle.[20] Eaton et al. (2016b) use a Ricardian model with input linkages to evaluate the driving forces behind the 2008–2009 trade collapse, while Eaton et al. (2016a) examine the role of trade frictions in generating classic international macroeconomic puzzles. Reyes-Heroles (2016) uses a similar model to quantify the role of declining trade costs in explaining increases in trade imbalances over time. Also focusing on trade imbalances, Bems (2014) discusses how input–output and value-added trade data can be used to properly calibrate multisector macro models.

The takeaway from this brief tour of the recent literature is that measurement of input linkages matters because input linkages themselves matter for understanding both trade and macroeconomic phenomena. With that in mind, I turn in the next section to discussing the current state of data on global input–output linkages.

[20]In related work, Duval et al. (2016) examine the role of value-added exports in explaining business cycle synchronization, de Soyres (2017) studies the role of input trade in generating productivity comovement across countries, and Steinberg (2017) studies the role of input linkages in explaining changes in portfolio home bias.

2.6. Data Sources

In the past decade, there has been rapid progress in the measurement of input–output linkages across countries. At present, there are at least six major sources of data—the GTAP Database, the Institute of Developing Economies and Japan External Trade Organization (IDE-JETRO) Asian Input–Output Tables, the World Input–Output Database (WIOD), EXIOBASE, the Eora Database, and the Organisation for Economic Co-operation and Development (OECD) Inter-Country Input–Output Tables—and more are in development (e.g., the Eurostat FIGARO project).[21] Although this review is not the place to exhaustively describe these data sources, I touch on some features and shortcomings of them below. Most of my commentary focuses on general data problems that researchers face in this area, highlighting where progress has been made and where more work is needed.

To construct a global input–output table, one must collect and combine raw data from a variety of sources, including supply and use data from country-level input–output accounts, time series data on production and expenditure from the national accounts, and disaggregate bilateral trade data. These underlying data are imperfect in several senses. In some cases, input–output data are literally unavailable for many countries for significant intervals of time. At best, input–output data are produced only for benchmark years, which are often asynchronous across countries. Technical features of the input–output tables (e.g., sector classifications or price concepts used in recording data) also differ across countries, and input–output data can be hard to reconcile with national accounts aggregates.

For all of these reasons, converting raw data into polished global input–output tables requires an arduous data cleaning, reconciliation, and extrapolation process. There are no unique right answers to the many questions that must be addressed, so the major data sources all use different methods for compiling their data. Going forward, it would be useful to know more about the consequences of various decisions and the possible scope for convergence in methods and statistical infrastructure. Furthermore, while existing data sources have been developed by academic research consortia, more involvement by national and international statistical authorities to institutionalize the data production process would have high value.

Beyond these basic matters, there are three broad issues that deserve more attention. The first two concern data coverage. First, input–output data sources currently cover the post-1990 period due to the wider availability of input–output data for recent decades. While this period is undeniably interesting, it is helpful to push backwards in time to gain perspective on more recent developments. The OECD has collected input–output tables for selected countries dating back to 1970, which have been used by Hummels et al. (2001) and Johnson & Noguera (2017) to measure vertical specialization and value-added exports over time. Furthermore, the IDE-JETRO Asian Input–Output Tables collect data for Asia dating back to 1985, prior to the emergence of China as a regional economic power. More work to collect data and extend analysis of GVCs backward in time would be valuable.

The second data coverage issue concerns aggregation. Most data sets have been constructed at a level of aggregation that is higher than that available in primary sources, partly to resolve industry concordance issues across sources, countries, and years. Nonetheless, it would be useful to have more disaggregated data on GVC linkages because policy decisions are often made at a more disaggregated level than existing data allow us to analyze. As an extreme example, trade policy is made at the tariff-line level (with thousands of tariff lines), while standard data sets have

[21] Several of these research projects are described in a special issue of *Economics Systems Research* (Volume 25, Number 1, 2013). The introductory paper by Tukker & Dietzenbacher (2013) provides a useful overview.

on the order of 40–50 industries. Developing methods to use all the disaggregated input–output, production, and trade data that exist, perhaps along the lines that the Eora and EXIOBASE projects have pursued, could be valuable for making the data policy relevant.

The third general issue is that there is less information in raw data sources about imported input use than first meets the eye. To build an accurate picture of GVCs, we need to be able to identify inputs in international trade data and then to track those inputs to users behind the border. Identifying inputs in trade data is relatively straightforward. The most compelling approach is to use a classification scheme, such as the Broad Economic Categories (BEC), to identify inputs versus final goods in disaggregated bilateral trade data.[22] This approach is used by the WIOD data set; other data sets use proportionality assumptions and/or mathematical optimization algorithms to impute bilateral input flows. Furthermore, bilateral services trade data are problematic: Services trade is measured poorly relative to goods trade, and there is no analog to the BEC approach for services. Basic improvements in national statistical frameworks are needed to address both of these issues.

Matters are arguably even more problematic behind the border.[23] One problem is that the use table in the input–output accounts—which tracks how commodities are used as inputs by individual industries—does not distinguish between patterns of input use for domestically produced versus imported goods and services. This implies that one must use assumptions (or data imputation techniques) to decompose input use across sources. Most commonly, imported input use tables are constructed using proportionality (alternatively, import comparability) assumptions, under which imported inputs are allocated across sectors in the same proportion as domestic goods.[24] Furthermore, the proportionality assumption is naturally applied to total imports, so inputs from all bilateral trade partners are treated in the same way. In plain language, the input–output segment of the national accounts does not directly tell us how much imported steel is used in US car production, nor whether imported steel from Canada and imported steel from Japan are used in the same way.

A second problem is that imported inputs are assumed to be used with equal intensity in industry-level production for domestic and export markets. When imported input intensity differs across firms within an industry, using the average input intensity reported in input–output tables to represent production techniques may lead to large biases in measurement of the value-added content of trade and other GVC metrics. This problem is obvious for countries that have large export processing sectors, such as Mexico or China. However, the problem is likely to be pervasive because participation in exporting is strongly positively correlated with participation in importing at the firm level.

Both of these problems in tracking inputs behind the border obscure the microeconomic details of GVCs. I return to a discussion of how microdata might be useful in dealing with these

[22]The BEC system is designed to classify traded goods, themselves classified according to the Standard Industrial Trade Classification or Harmonized System, into consumption goods, intermediate goods, and capital goods categories, as defined in the System of National Accounts. Eurostat advocates the use of BEC-classified trade data for the construction of imported input use tables (Eurostat 2008).

[23]As Horowitz & Planting (2009, p. 6-1) disconcertingly put it, "the estimation of transactions [flows between establishments or from an establishment to a final user] is often referred to as 'the art of input-output.' 'Art' is needed because of the paucity of data for measuring transactions in many areas."

[24]Put differently, aggregate input use patterns in the use table are assumed to apply to both domestically produced and imported inputs. This assumption is often applied in the data at a higher level of disaggregation than that of the resulting published import use table, which means that proportionality does not hold in published data. Application of proportionality at the most disaggregate level possible is desirable.

problems in Section 4. With that objective in mind, in the next section, I turn to micro approaches to measuring GVCs.

3. MICRO APPROACHES TO MEASURING GLOBAL VALUE CHAINS

Alongside efforts to measure GVC linkages using input–output data, census data, customs data, and firm surveys have been applied to advance measurement of GVC linkages at the firm level. Superficially, this micro approach to measuring GVCs may appear disconnected from the input–output approach in Section 2. Under the surface, however, there are important points of contact between the two research agendas.

To tie the input–output and microdata approaches together, it is useful to think through a hypothetical disaggregation of the global input–output table. Instead of measuring industry-level shipments, suppose that we could measure firm-to-firm transactions.[25] That is, suppose that we observe input shipments from firm f' in sector s' in country i to firm f in sector s in country j: $z_{ij}(s', s; f', f)$. Furthermore, suppose that we observe shipments by firm f in sector s of country i to final users in country j: $f_{ij}(s; f)$. With $z_{ij}(s', s; f', f)$ and $f_{ij}(s; f)$, we could then build a global input–output table at the firm level, in which columns describe how firms source their inputs (i.e., what inputs does each firm buy and from which countries), while the rows describe where a firm sells its outputs (to which final or intermediate users, to which downstream firms, to which countries). This hypothetical firm-level data would then aggregate up to industry-level input–output tables.

This thought experiment helps explain how firm-level data can improve measurement of GVC linkages. It also serves to identify limitations of firm-level data for understanding GVCs. A key strength of firm-level data is that we can observe transactions between firms and their foreign partners, rather than inferring them by combining industry-level information with trade data (as in the input–output accounts). Furthermore, firm-level sources capture heterogeneity in GVC linkages across firms, which is obscured by aggregated industry-level data. I emphasize these strengths in describing how firm-level data have been applied to measuring offshoring and/or input sourcing, vertical specialization in trade, and the GVC activities of multinational firms. Firm-level data are also limited in some important respects. Most importantly, firm-level data do not contain the full set of firm-level shipments [$z_{ij}(s', s; f', f)$ and $f_{ij}(s; f)$] needed to map out the complete global production process. I discuss these points of strength and weakness in more detail below and continue this discussion in Section 4.

3.1. Offshoring and Input Sourcing

Since the mid-1990s, offshoring—the replacement of domestic sources of inputs and business tasks with foreign (offshore) sources—has occupied a central place in the literature and policy discussions. Feenstra & Hanson (1996, 1999) defined offshoring in terms of the share of foreign inputs in total input use and thus launched an important empirical literature on the consequences

[25]To simplify the discussion, I omit notation necessary to accommodate multiproduct firms whose products span multiple industries. Because multiproduct firms are important in the data, empirical efforts to construct input–output tables from firm-level data must confront complications that arise due to their existence. One challenge is that one needs to observe shipments by firm and product within a country to construct aggregate cross-industry shipments, and these data are not always available. A second challenge is that data on imported input use are recorded at the firm level but not broken down by the products for which they are used as an input.

of foreign input sourcing.[26] While much of this literature has focused on the labor market impacts of offshoring, I define the offshoring and input sourcing literature broadly to encompass work on the impact of imported inputs on general firm performance (e.g., productivity and growth), as well.

To maintain focus, I restrict my attention to recent work that has examined offshoring and input sourcing at the firm level, which draws on the (relatively new) availability of data sets linking firm-level variables (production, employment, materials use, and so on) to firm-level import transactions.[27] Connecting to the discussion above, these data sets allow us to observe either bilateral or multilateral input purchases from foreign sources for individual firms—i.e., $\sum_{f'} z_{ij}(s', s; f', f)$ or $\sum_i \sum_{f'} z_{ij}(s', s; f', f)$, depending on the data source.[28] Various lines of work exploit this granular perspective on input sourcing to study the impact of imported inputs on firm prices, productivity, revenue, and domestic employment.

A common theme in this work is that a firm that imports is able to lower its unit costs through access to lower cost inputs, a larger variety of inputs, or higher-quality inputs.[29] These unit cost reductions lead firms to expand and appear more productive (Blaum et al. 2018, Halpern et al. 2015), and they can induce further complementary cost-reducing research and development (R&D) investment (Bøler et al. 2015). They may raise or lower domestic employment depending on the substitutability of domestic workers with imported inputs (Hummels et al. 2014). The fact that unit costs fall as firms add foreign suppliers also yields complementaries in input sourcing across markets (Antràs et al. 2017). Running this process in reverse, we see that shocks that lead firms to drop foreign suppliers (such as exchange rate changes) can lead to reductions in firm and thus aggregate productivity, as emphasized by Gopinath & Neiman (2014).

One nice feature of this collected body of work is that it has combined both structural and reduced-form methods to describe the role of input sourcing. For example, Bøler et al. (2015) analyze the impact of a change in R&D tax credits in Norway, which capped the new tax credit in value such that only some firms were able to take advantage of it. This feature of the reform allows Bøler et al. to provide reduced-form difference-in-differences evidence that R&D complements importing at the firm level: Firms incentivized to undertake more R&D also raise imports of intermediate inputs relative to control firms. Building on the model of endogenous importing and structural estimation procedure developed by Halpern et al. (2015), Bøler et al. then structurally estimate a model with endogenous R&D and import decisions to quantify total returns to R&D and imports, accounting for complementaries between them.

[26]As discussed in Section 2.2.1, input–output-based measures of domestic versus foreign value-added content in final goods can also be used to measure offshoring and in fact are conceptually consistent with prominent models of offshoring and task trade. In particular, they account for the fact that foreign-sourced inputs may contain domestic content, while domestically sourced inputs may contain foreign content. Beyond this comment, I do not repeat this discussion in this section; instead, I focus entirely on domestic versus foreign sourcing of inputs, as in the literature.

[27]A few words on the scope of my discussion are warranted. I omit work that measures offshoring at the industry level, either using input–output data (as in Feenstra & Hanson 1996, 1999; related work) or using firm-level data aggregated to the industry level [as in the work of Ebenstein et al. (2014)]. I also largely omit work that examines the impact of tariff changes on firm performance—in particular, work that studies the impact of input tariff liberalization on productivity or product growth at the firm level (Amiti & Konings 2007, Goldberg et al. 2010, Topalova & Khandelwal 2011). All of these studies have significant value for understanding the impact of GVC integration on workers and firms; I omit detailed discussion of them only due to space constraints.

[28]While s denotes industries, transactions are often available at a level of commodity disaggregation (e.g., at the Harmonized System six-digit level) far beyond what is available in industry-level input–output data sources.

[29]While the literature has placed emphasis on offshoring, any shift from in-house to outsourced production lowers firm costs. Fort (2017) analyzes firm decisions about whether to fragment production at home or abroad.

Antràs et al. (2017) also combine structural estimation of their model with counterfactual analysis, focusing on analysis of China's post-2001 export surge. Specifically, they benchmark the prediction of the model—that firms adding China as an import source in response to the shock should also add additional domestic and import sources—to data using both descriptive statistics and regression analysis of changes in firm-level sourcing behavior.

Finally, Hummels et al. (2014) exploit heterogeneity across firms in input sourcing patterns interacted with shocks to transportation costs and export supply to generate firm-specific instruments for the use of imported inputs. Using matched worker and firm data on employment and wages in Denmark, they establish that offshoring is associated with contractions in domestic employment, particularly for low-skilled workers, and a decline in the relative wage of low-skilled workers.

Returning to the broader theme of measuring GVCs, one shortcoming in this literature is that input sourcing is only a narrow slice of the firm's overall GVC strategy, focused on the firm's decision about sourcing upstream inputs. Moreover, the term offshoring often evokes quite different ideas: the movement of downstream stages (final assembly) to low-wage locations or the complete closure of domestic production facilities. This downstream offshoring manifests itself in an entirely different way in the data, as firms shifting toward exporting inputs and reimporting final goods, as purchases of contract manufacturing from abroad, or as the closure and transition of manufacturing establishments. Bernard & Fort (2015, 2017) touch on the last dimension of this problem in their work on factory-less goods producers, who organize the production process (providing R&D, management, and distribution services) and contract out production to foreign firms. These issues are also discussed in work on multinationals and processing trade, where we can observe (to an extent) whether exports are processed abroad and embodied in reimported final goods. More work on incorporating these additional perspectives on offshoring with the input sourcing–based offshoring literature would be helpful.

A second limitation of this literature is that it provides evidence only on the direct impact of input sourcing decisions and misses how higher-order interconnections among firms matter for understanding and quantifying the impacts of offshoring. For example, the cost reduction at a firm that starts importing inputs is passed down through the value chain to firms that use that firm's output as an input. These interconnections lie at the heart of the hypothetical firm-level input–output table discussed above. They clearly operate behind the border domestically, but they may also extend across borders—e.g., an automobile parts supplier in Ohio may lower costs by offshoring some production, which may then benefit a Canadian engine producer, which ultimately supplies an engine to a car assembly plant in Detroit. I return to recent work that has started to address these linkages below.

3.2. Joint Exporting and Importing

Importers are also exporters. This is both an empirical statement—import and export status are strongly positively correlated at the firm level—and an admonition to remember that exports are a sign of participation in GVCs, as well.

To back the empirical statement, Bernard et al. (2008, 2018a) document correlations in export and import status for the United States, emphasizing that firms that both import and export (while few in number) account for 90% of US trade.[30] This correlation is not hard to rationalize from

[30]To my knowledge, similar patterns are apparent in every firm-level data set thus far examined. For a nonexhaustive set of references, the reader is referred to Amiti & Davis (2011) on Indonesia, Kasahara & Lapham (2013) on Chile, Amiti et al. (2014) on Belgium, and Blaum (2017) on Mexico.

a theoretical perspective, at least qualitatively. First, to the extent that firms face fixed costs in accessing both export and import markets, the most productive firms will naturally self-select into both importing and exporting. Second, exporting and importing are complementary: Importing lowers firm costs (raising revenue), making it easier for firms to cover the fixed costs of exporting, and export entry raises firm revenue, which makes it easier for firms to cover fixed import costs, as well.

While joint exporting and importing is pervasive, it is particularly important for firms engaged in processing trade. Processing trade typically occurs under a special legal regime, under which firms are exempt from import duties if they export their output. Depending on the country, processing firms may also benefit from (nontariff) tax incentives, input subsidies, or other policies.

Processing trade regimes are ubiquitous: The International Labor Organization counted over 130 countries with laws providing for export processing zones in 2006, up from only 25 in 1975 (Boyenge 2007). Grant (2017) reports that there are over 300 foreign-trade zones in the United States, accounting for 13% of US manufacturing output and $288 billion in imports, while Cernat & Pajot (2012) report that exports originating from the European Union inward processing regime account for 10% of total EU exports.[31]

While this developed country processing trade is significant and understudied, it is dwarfed by emerging market processing trade. In China, for example, more than half of total exports originate from processing trade firms. Kee & Tang (2016) use firm-level data for processing and nonprocessing exporters to build estimates of Chinese and foreign content in China's exports. The difference between exports and imported inputs for a processing firm is a rough estimate of the Chinese content embodied in processing exports, which includes both direct value added by the processing firm and indirect value added by upstream Chinese suppliers to the processing firm.[32] Kee & Tang estimate that Chinese value added accounted for 45–55% of the value of China's processing exports between 2000 and 2007, with a rising trend over time due to substitution of foreign for Chinese inputs. This is naturally lower than Chinese content in its nonprocessing exports, which was near 90%.

Whether integration into global value chains via export processing is good policy is less clear. Interestingly, Dai et al. (2016) show that Chinese firms that select into the processing trade sector are actually less productive than ordinary exporters, a result that they attribute to lower fixed costs of exporting and industrial policies that favor processing firms. Whether this pattern holds elsewhere is unknown; if it does, it suggests that countries are effectively subsidizing unproductive firms via their processing trade regimes, which implies that expansion of processing trade may not be a healthy sign. Importantly, it is also an open question whether there are dynamic gains to be had from encouraging processing exports, which could offset these concerns. Additional work in China and other countries with large processing regimes (e.g., Mexico) is much needed.

Turning back to measurement of GVCs, consider two final observations. First, to the extent that the domestic content of processing exports differs vastly from that of nonprocessing exports,

[31]While these figures describe inward processing regimes, in which domestic firms import inputs to produce exports, both the United States and the European Union also have outward processing regimes, in which exported intermediate goods may be processed abroad and taxes are paid only on the foreign value added embodied in those reimported final goods (for work on the 9802 Program in the United States, see Feenstra et al. 2000).

[32]This statement requires that inputs from nonprocessing Chinese firms used by processing exporters be produced entirely in China (with no foreign content themselves) and that imported inputs contain no Chinese content. Kee & Tang (2016) use input–output data to argue that the Chinese content of inputs imported by processing firms is plausibly zero, and they incorporate input–output estimates of the foreign content of inputs from nonprocessing firms in their estimates. Kee & Tang also estimate the domestic content of nonprocessing firms using an assumption that firms split imported inputs proportionally across domestic sales and exports.

it is prima facie important to take processing trade into account in computing the value-added content of trade, as well as other input–output-based measures of GVC linkages. Second, while processing trade is a stark example of the high concentration of importing and exporting activities within a few firms, it is typically the case that exports are produced by firms that import intensively. As such, the type of issues that arise in measuring GVC linkages for processing exports are likely more general. I return to both of these thoughts in discussing avenues for research below.

3.3. Multinational Firms

Multinationals are the vehicles through which most trade—and thus input trade—takes place. In this section, I want to highlight a few aspects of multinational data that are particularly relevant for mapping value chains, with emphasis on the US multinational data produced by the Bureau of Economic Analysis (BEA).[33]

With BEA data, it is possible to map out vertical production networks between domestic parents and foreign affiliates, which entail task specialization within the multinational enterprise and correspondingly lead to flows of inputs between parents and affiliates (Hanson et al. 2005). Specifically, the data contain shipments from parents to affiliates, broken down according to intended use (e.g., for further processing, resale, or as a capital input). Furthermore, for a subset of large affiliates, the data contain shipments by affiliates to different types of buyers—e.g., to the parent, US buyers other than the parent firm, or buyers in third countries. As such, they provide information about how inputs are used in the destination, unlike census- or customs-type data. In this sense, these data allow us to see a subset of the bilateral network of firm-level shipments [$z_{ij}(s', s; f', f)$ and $f_{ij}(s; f)$] that underpin the hypothetical firm-to-firm global input–output table.

Ramondo et al. (2016) document two facts using these data that speak to GVC linkages within multinationals. The first fact is that trade among parents and affiliates is highly skewed: The median manufacturing foreign affiliate does not ship anything to or from its parent, while the largest 5% of affiliates account for half of transactions with the parent. This is prima facie surprising: The majority of parent–affiliate pairs have de minimus vertical GVC linkages with one another. Building on this observation, Ramondo et al. also show that vertical GVC linkages within multinationals are not necessarily where we would a priori expect them to be. While US parents tend to own affiliates in industries that are vertically linked to the parent's industry, the magnitude of input–output linkages between the industries does not predict actual transactions between parent and affiliate. This second fact is also puzzling: We should expect to find microevidence of GVC linkages where input–output data tell us to look for it. Overall, these data raise many new questions about how to link micro and macro perspectives on GVC linkages.

Despite these puzzling results, the information on how parents are linked to affiliates in the BEA data has been put to good use for studying GVC linkages. Hanson et al. (2005) use the data to study the determinants of vertical linkages, demonstrating that trade costs reduce affiliate use of inputs from parent firms, while low unskilled wages tend to increase them (consistent with the idea that affiliates are engaged in processing trade). Harrison & McMillan (2011) instead use measures of vertical linkages to examine how domestic employment at multinationals responds to the engagement of these multinationals with foreign affiliates. Unconditionally, they find that affiliate employment in low-income countries substitutes for domestic employment. However, domestic employment increases as foreign wages fall when parents send inputs for further processing

[33] The literature on multinationals is vast, so I cannot cover it in depth in this review. The reader is referred to recent surveys by Yeaple (2013) and Antràs & Yeaple (2014) for a more complete view of the literature.

to their affiliates in developing countries. Both contributions demonstrate the value of being able to observe how exports are used abroad in testing theories of value chain fragmentation.

4. PUSHING FORWARD

While there has been ample progress in measuring GVC linkages at both the macro and micro levels, this important work is incomplete. Supplementing my discussion about gaps in the literature in Sections 2 and 3, I conclude by discussing two broad areas in which more work is needed.

4.1. Linking the Micro and Macro Approaches

The macro and micro approaches to measuring GVC engagement have advanced on largely parallel tracks, headed in the same direction, but with limited overlap. There is scope for convergence in these two tracks, however: Microdata can improve the input–output approach, and input–output-type analysis can strengthen microquantification exercises.

In Section 2.6, I note that there is less information on input use in the national input–output accounts than meets the eye. One reason for this is that national accountants do not actually ask firms detailed questions about domestic versus foreign sourcing in the surveys that underlie the input–output accounts. While directly enhancing data collection would be the best solution, there are a number of ways that creative use of existing data sources might greatly improve measurement of GVC linkages.

First, existing microdata on import transactions linked to firm census-style data could be brought to bear on improving estimates of the allocation of imported inputs across sectors. Using notation from the hypothetical firm-to-firm global input–output table, we observe imported inputs at the firm level—like $\sum_{f'} z_{ij}(s', s; f', f)$—in microdata. Aggregating firm-level imports to the industry level—$\sum_f \sum_{f'} z_{ij}(s', s; f', f)$—ought to yield a good estimate of bilateral input trade $z_{ij}(s', s)$.[34]

Building on this idea, Feenstra & Jensen (2012) attempt to construct an industry-to-industry import input–output table using the US Linked/Longitudinal Firm Trade Transaction Database. The good news is that they find that the resulting import input–output coefficients $[z_{ij}(s', s)/y_j(s)]$ are positively correlated with existing published data from the BEA, with an unweighted correlation of 0.68 and a value-weighted correlation of 0.87. Thus, existing import input–output tables may not be so bad after all. However, there are deviations between the two data sets, which implies that there may be additional information in the microdata that could be profitably combined with existing input–output data sources to yield a better composite (reconciled) table.

The second way that microdata could improve input–output data is by enabling disaggregation of input–output tables, thus tracking GVC linkages at higher resolution. In industry-level input–output analysis, one effectively makes the assumption that there is a representative producer in each industry operating with a technology that reflects industry averages, the output of which is distributed across sectors and end uses based on average use patterns. Failure of this representative producer assumption leads to bias in input–output analysis. For example, one empirically relevant concern is that exports tend to be produced with a higher imported input intensity than the average unit of output in most industries, as implied by the concentration of trade among firms

[34] I say ought to because there are limitations in firm-level data that make the concordance to input–output-based estimates imperfect. Nonetheless, the principle that there is additional information in firm-level data that is not currently incorporated into input–output analyses stands.

that both import and export (see Section 3.2). Ignoring this specific correlation would lead one to underestimate engagement of exporting firms in GVCs and the import content of exports, thus overestimating the value-added content of trade.

In a first-best world, national accountants would routinely construct separate input–output tables that address relevant dimensions of heterogeneity.[35] Until that happens, we must make due with existing data. Fortunately, there has been some progress in using existing data sources to allow for correlations in input use and output use patterns across firms within industries. Koopman et al. (2012) develop a procedure to split consolidated input–output tables into separate input–output tables for processing versus nonprocessing firms using industry-level trade and GDP data broken down by firm type. They report that the share of domestic value added in Chinese exports falls from 75% to 54% when using the adjusted split table in place of the consolidated input–output table, which indicates that aggregation bias is large when processing trade is prevalent.

More broadly, it would be useful to explore how census and customs data could be used to build extended input–output tables for exporting versus nonexporting firms in all countries, with or without processing trade regimes. This work could proceed either building on the direct data aggregation approach of Feenstra & Jensen (2012) or using the data imputation approach of Koopman et al. (2012). Pushing still further, firms that differ in national ownership may also differ in their input use and output allocation—e.g., affiliates of multinationals likely have larger-than-average input use and export sales vis-à-vis the country of their parent firm—and microdata can to be applied to address this heterogeneity, as well.[36] With continued development, the end goal ought to be to include extended input–output tables in published global input–output tables.

Turning to a different kind of aggregation issue, we see that concepts from the input–output literature are useful for aggregating microevidence on the consequences of foreign input sourcing to the macro level. As in Section 3.1, recent work that evaluates the consequences of foreign input sourcing at the firm level measures the direct impact of foreign sourcing, answering the question of how much a firm's performance changes when it starts sourcing from abroad, all else being constant. While these direct effects are a good starting point, there are also important indirect spillovers across firms: Firms benefit not only from their own foreign sourcing, but also from the foreign sourcing of their domestic suppliers. Thus, the domestic input–output network transmits and likely amplifies the direct effects of foreign sourcing.

To allow for both direct and indirect effects, one ideally needs data on the network of domestic firm-to-firm input–output linkages $[z_{ii}(s', s; f', f)]$. As above, the first-best solution would be to collect these data on these linkages. Recent work that exploits value-added tax data (Bernard et al. 2017, Tintelnot et al. 2017), firms' self-reported buyers and sellers (Barrot & Sauvagnat 2016, Bernard et al. 2018b, Carvalho et al. 2016, Furusawa et al. 2017), or survey data on intranational shipments (Atalay et al. 2014) is pushing in this direction.

Unfortunately, these micronetwork methods are unlikely to be universally applicable due to lack of data availability. Proxy methods that combine existing macro and micro approaches to measurement are a useful tool in this area, as well. Specifically, aggregate industry-to-industry linkages $[z_{ii}(s', s)]$ can serve as a proxy for firm-to-firm linkages. Blaum et al. (2018) provide a model with heterogeneous firms embedded in industry equilibrium, in which industries (and thus the firms in those industries) are linked together as in input–output data. Using the model, they

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[35]For example, in countries with large processing trade sectors, it should be possible to construct input–output tables that distinguish processing from nonprocessing firms within each industry. As proof of concept, there exists one year (2003) in which such input–output data is available for Mexico (see Cruz et al. 2013).

[36]Again focusing on China, Ma et al. (2015) construct extended input–output tables that distinguish foreign from Chinese-owned firms, while Tang et al. (2017) distinguish between state-owned and private enterprises in China.

quantify how changes in foreign sourcing at the firm level aggregate up to the macro level and find that input–output linkages behind the border are quantitatively important for understanding how aggregate industry-level prices change following shocks to foreign sourcing. More work combining macro and micro approaches to measuring GVC engagement would be most welcome.

4.2. Theory and Measurement

My final point is that GVC measurement and theory are linked: Theory guides what has been measured, and improved measurement has stimulated new theory. Yet there remains fertile ground for further work in areas where theory and measurement remain far apart.

One area where theory is ahead of measurement is in conceptualizing the microstructure of value chains. Among models of value chains, there is an important distinction between models that feature sequential production chains and those that adopt a modular or roundabout production structure. In a sequential production chain, upstream stages in the production process are a direct input to (and thus must be performed prior to) downstream stages, as in an assembly line. In a modular production model, inputs are produced independently and then aggregated to produce output. Furthermore, the widely used roundabout production structure, in which output is used as an input production, is effectively a modular production process with a loop in it. These seemingly esoteric features of the production process matter a lot in practice because they deliver distinct predictions about the impact of frictions on trade (Baldwin & Venables 2013, Yi 2003) and spillovers within value chains (Costinot et al. 2013).

While the language of input–output analysis—which refers to the length of and location of producers in value chains (Section 2.3)—suggests sequentiality in production, input–output data are also consistent with modular or roundabout production. In fact, modular or roundabout production is the default approach to modeling GVC trade. Neither input–output data nor census or customs firm-level microdata alone include information that can distinguish sequential value chains from modular or roundabout production. One approach to doing so entails confronting existing data with models that nest the two production alternatives and comparing the models based on their distinctive predictions. A second approach would be to develop new measures of sequentiality in production at the sector level, akin to attempts to measure product differentiation or contractability. In the end, both approaches are likely to be necessary to evaluate the role of sequential production in the global economy.

A second area where theory and measurement remain far apart is in understanding the organization of value chains at both the firm and industry levels. At the firm level, for example, Antràs & Chor (2013) provide a property-rights theory of the firm that yields predictions for how firms will choose to integrate versus outsource stages in GVCs. While Alfaro et al. (2015) test this theory by inferring how parents and affiliates are linked to one another from input–output data, Ramondo et al. (2016) cast doubt on whether aggregate input–output linkages are useful for understanding the actual transfer of resources within multinational firms (see Section 3.3). Ideally, improved data collection on the activities of multinationals—crucially, the operations of affiliates and their interactions with nonaffiliate suppliers at home and abroad—could greatly enhance our understanding of multinational firms in a value chain context. Furthermore, firm-level survey data that are tailored to answering questions about offshoring or outsourcing activities could also have high value in this area.[37]

[37] Fontagné & D'Isanto (2017) provide an example of a survey targeted at identifying motives for offshoring and integration versus outsourcing.

The case study method can also complement input–output and microdata methods for studying GVCs. Case studies have already served to motivate central GVC concepts—e.g., product teardown studies of the Apple iPod and other consumer electronics were influential in motivating value-added trade concepts (Dedrick et al. 2009).[38] Industry case studies can shed light on the industrial organization of GVC activities, as in the work by Gary Gereffi and coauthors (Gereffi 1999, Sturgeon et al. 2008) on apparel and automobile value chains. The organizational and institutional details contained in these case studies are a rich font for GVC theory. Furthermore, quantitative work in the style of the industrial organization literature—focusing on industries where one can gather high-quality data, understand the market, model interactions between firms carefully, and respect and exploit particular features of the production process—would add value relative to existing approaches to studying GVC activities.

5. APPENDIX

This section expands on the discussion in Section 2.2.2 about measuring value-added content in exports. I begin by rederiving value added in exports, emphasizing that analyzing exports amounts to uncoupling the global input–output system. I then discuss how decomposing value-added content in exports is part of an overall decomposition of GDP.

In Equation 7, input shipments $\mathbf{A}_{12}\mathbf{y}_2$ have been removed from the global input–output matrix and deposited into exports. This operation uncouples output in country 1 and country 2: $\mathbf{y}_1$ depends directly on $\mathbf{f}_{11}$ and $\mathbf{x}_{12}$ but (conditional on $\mathbf{x}_{12}$) does not directly depend on $\mathbf{y}_2$.[39] As a result, output for country 1 can be uniquely decomposed according to whether it is used to produce $\mathbf{f}_{11}$ or $\mathbf{x}_{12}$:

$$\mathbf{y}_1 = [\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{f}_{11} + [\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}, \qquad 27.$$

where $[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}$ is the value of output from country 1 required to produce its exports. Correspondingly, the amount of value added from country 1 required to produce its exports is $\mathbf{xc}_{11} = \hat{\mathbf{v}}_1\hat{\mathbf{y}}_1^{-1}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}$.

Pushing this logic further, we can see that output in country 2 depends on output in country 1:

$$\begin{aligned}
\mathbf{y}_2 &= \mathbf{A}_{21}\mathbf{y}_1 + \mathbf{A}_{22}\mathbf{y}_2 + \mathbf{f}_{21} + \mathbf{f}_{22} && 28.\\
&= \mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12} + \mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{f}_{11} + \mathbf{A}_{22}\mathbf{y}_2 + \mathbf{f}_{21} + \mathbf{f}_{22} && 29.\\
&= [\mathbf{I} - \mathbf{A}_{22}]^{-1}\mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12} + \left[[\mathbf{I} - \mathbf{A}_{22}]^{-1}\mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{f}_{11} + [\mathbf{f}_{21} + \mathbf{f}_{22}]\right]. && 30.
\end{aligned}$$

In Equation 28, note that $\mathbf{A}_{21}\mathbf{y}_1$ is the vector of inputs shipped from country 2 to country 1 for all downstream uses. In Equation 29, I substitute for $\mathbf{y}_1$ using Equation 27 to identify the subset of those inputs that are used to produce country 1's exports: $\mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}$. In Equation 30, I pull $\mathbf{y}_2$ to one side. The result is a decomposition of country 2's output, where $[\mathbf{I} - \mathbf{A}_{22}]^{-1}\mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}$ is the amount of country 2's output needed to produce the inputs that it ships to country 1 that are ultimately embodied in country 1's exports. From this, it is straightforward to see that country 2's value added in $\mathbf{x}_{12}$ is $\mathbf{xc}_{21} = \hat{\mathbf{v}}_2\hat{\mathbf{y}}_2^{-1}[\mathbf{I} - \mathbf{A}_{22}]^{-1}\mathbf{A}_{21}[\mathbf{I} - \mathbf{A}_{11}]^{-1}\mathbf{x}_{12}$.

[38] The iPod example was picked up by Johnson & Noguera (2012a), whose work was, in turn, stimulated by Varian (2007). Notable failures in value chain functioning have also served to highlight risks inherent in GVCs, as in the problems Boeing encountered in managing its global supplier network for the Dreamliner (Gates 2013) or the fragility of automobile supply chains to disruptions in the supply of critical parts exposed in the aftermath of the Japanese Tohoku earthquake and tsunami (Lohr 2011, Matsuo 2015).

[39] This is consistent with the observation by Los et al. (2016) that we can compute domestic value added in exports using input–output tables for one country at a time.

It is useful to explain how value-added content in exports fits into a full decomposition of GDP. Using Equation 7, note that

$$\begin{bmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \end{bmatrix} = \hat{\mathbf{v}}\hat{\mathbf{y}}^{-1} \begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix} = \hat{\mathbf{v}}\hat{\mathbf{y}}^{-1} \left[\mathbf{I} - \mathbf{A}^*\right]^{-1} \mathbf{F}^* + \begin{bmatrix} \mathbf{xc}_{11} \\ \mathbf{xc}_{21} \end{bmatrix}.$$

Thus, value added in exports is naturally only one component of country 1's overall value added. The other component is value added embodied in final goods contained in $\mathbf{F}^*$, which excludes $\mathbf{f}_{12}$ because it is already contained in $\mathbf{x}_{12}$.

One subtle but important point to note is that the resulting decomposition of value added in final goods will not (in general) match results obtained via the methods described in Section 2.2.1. Upon reflection, the reason is obvious. While we use the matrix $[\mathbf{I} - \mathbf{A}^*]^{-1}$ to compute the gross output needed to produce final goods in this section, we use the Leontief Inverse matrix $[\mathbf{I} - \mathbf{A}]^{-1}$ to compute output needed to produce final goods in Section 2.2.1. In Equation 3, output is decomposed according to where it is ultimately embodied in final goods. In contrast, in this section, we treat output required to produce input shipments $\mathbf{A}_{12}\mathbf{y}_2$ as part of the output needed to produce exports, which means that the calculation implicitly adjusts down the amount of output need to produce final goods. Put differently, output is decomposed in part based on where it is embodied in exports, rather than entirely based on where it is embodied in final goods.

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