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Hidden Exposure: Measuring US Supply Chain Reliance

ABSTRACT Supply chain problems, previously relegated to specialized journals, now appear in G7 Leaders' Communiqués. Our paper looks at three core elements of the problems: measurement of the links that expose supply chains to disruptions, the nature of the shocks that cause the disruptions, and the criteria for policy to mitigate the impact of disruptions. Utilizing global input-output data, we show that the US exposure to foreign suppliers, and particularly to China, is "hidden" in the sense that it is much larger than what conventional trade data suggest. However, at the macro level, exposure remains relatively modest, given that over 80 percent of US industrial inputs are sourced domestically. We argue that many recent shocks to supply chains have been systemic rather than idiosyncratic. Moreover, systemic shocks are likely to arise from climate change, geoeconomic tensions, and digital disruptions. Our principal conclusion is that the concerns regarding supply chain disruptions, and policies to address them, should focus on individual products rather than the whole manufacturing sector.

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When Harold Macmillan—the UK prime minister in the turbulent post-WWII years—was asked: “What is the greatest challenge you face?” his alleged reply was: “Events, my dear boy, events.” Events, termed “shocks” by economists, have reemerged as formidable challenges for global leadership, with supply chain disruptions being top of mind. At their May 2023 summit, for example, G7 leaders stated that “supporting resilient and sustainable value chains remains our priority” (European Council 2023, 1). It was not always like this.

Constructed in a time of stability and hope, today’s globe-spanning supply chains propelled efficiency and progress as they became the arteries of the US economy. US administrations supported the internationalization of supply chains with the entry into force of deep trade agreements, like the North American Free Trade Agreement on January 1, 1994, and the establishment of the World Trade Organization on January 1, 1995. At the time, international supply chains were viewed as enhancers of productivity and boosters of prosperity (CEA 2016).

But supply chains are behaving differently in the face of what Mervyn King and John Kay term “radical uncertainty” in their 2020 book of the same name. Today, reverberations of supply chain disruptions echo loud and long, influencing everything from laptop availability and headline inflation to national security and shortages of medicine that affect millions. Empirical studies of these effects are just emerging (Goldberg and Reed 2023; Boehm, Flaaen, and Pandalai-Nayar 2019; Carvalho and others 2021; Bonadio and others 2021). Most of the economic literature on global supply chains (GSCs) study factors that foster them (Grossman and Rossi-Hansberg 2008; Antràs 2020; Alfaro and Chor 2023) or investigate broader scale trends in the landscape of GSCs (World Bank 2020). Economic research on supply chain disruptions is appearing on the theory side (Grossman, Helpman, and Lhuillier 2021; Carvalho and Tahbaz-Salehi 2019; Elliott and Golub 2022; Elliott, Golub, and Leduc 2022; Baqaee and Rubbo 2023) and on the empirical side (Schwellnus, Haramboure, and Samek 2023a; Imbs and Pauwels 2022).

As these are early days for the economics of supply chain disruptions, there is no consensus on how to organize thinking about the related issues. We propose that the phrase “supply chain disruptions” inherently directs us toward a three-pillar organizing framework: the links that constitute GSCs, the shocks that disrupt them, and policies that mitigate or avoid the disruptions. Our paper is organized around these three pillars.

The rest of the paper comes in five sections. Section I looks at how we can measure the links. Section II shows our empirical findings on the exposure of US manufacturing sectors to domestic and foreign supply chain links, with a special focus on China (the largest foreign supplying nation). Sections III and IV present, respectively, frameworks for thinking about shocks and policy. Our concluding remarks are in section V.

I. The Links: On the Measurement of Supply Chain Exposure

In US manufacturing companies, supply chain risk managers have long recognized the importance of knowing their suppliers (Gurtu and Johny 2021). However, the advent of supply chain disruptions on a grand scale, spanning multiple sectors and nations, has elevated this issue from a firm-level concern to a nation-level concern. Identifying where things are actually made, however, is not as easy as it might appear.

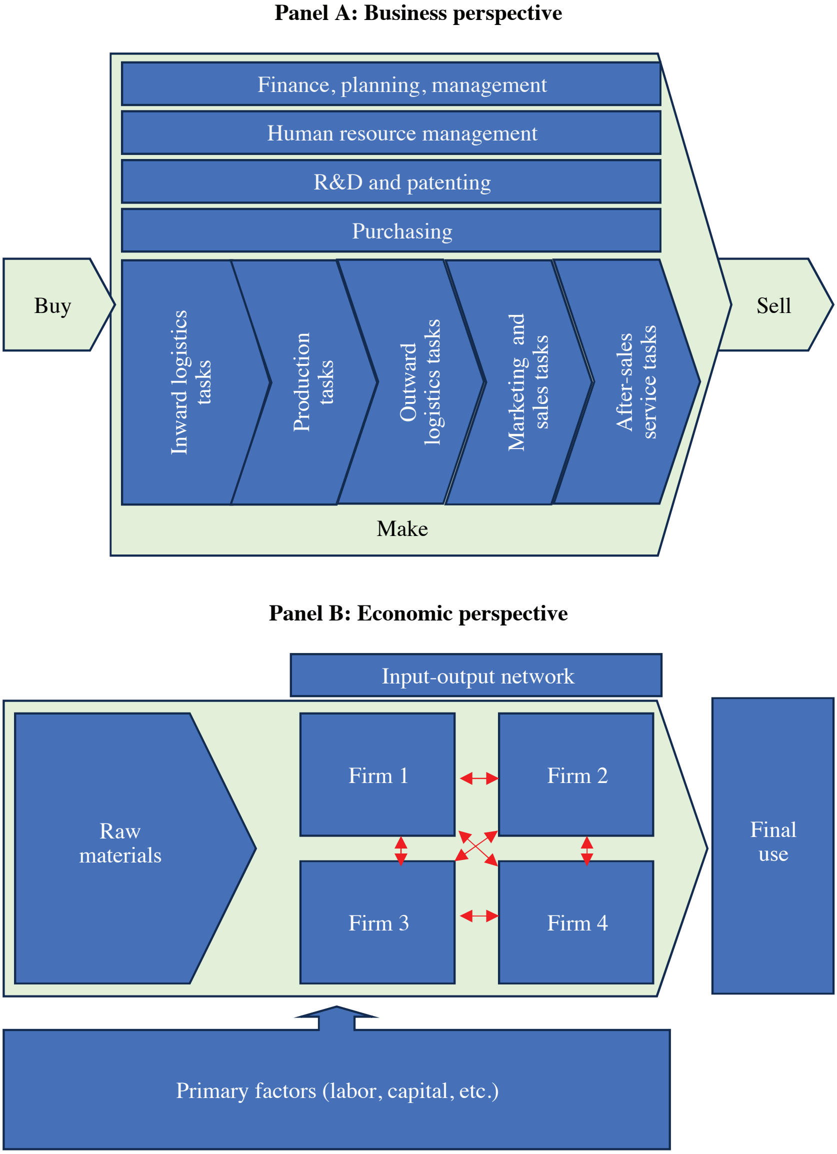
I.A. You Can't Fix What You Can't See: Two Ways of Looking at Supply Chains

A cornerstone contribution of our paper lies in the identification of the true origin of the manufactured inputs bought by US manufacturing sectors. We are not the first to tackle the problem. Many studies have taken what could be called the business value chain approach to trace out a firm's supply chain. Our paper presents measures of supply chain exposure that rely on a very different approach.

BUSINESS VALUE CHAIN APPROACH VERSUS ECONOMIC APPROACH Much of the excellent, detailed work on supply chain dependencies has used the business, or value chain approach. The Biden administration, for example, has set up a series of initiatives to map industrial supply chains (White House 2022) with an eye to revealing where potential weak points may lie. These initiatives take a business-focused approach inspired by Michael Porter (Porter 1985). At its core, this is based on a straightforward view that firms buy things to make the goods that they sell. The direct suppliers are called tier 1 suppliers, their suppliers are called tier 2 suppliers, and so on. This approach establishes a sequence, or chain, of supplying firms, which is why the literature uses the phrase "supply chain," or "value chain" when speaking about the network of suppliers (figure 1, panel A). This is quite different from the economic approach, as panel B of figure 1 illustrates.

Economists tend to take a bird's-eye view. The buy-make-sell logic of Porter's value chain is recursive, establishing an input-output network of firms selling to firms and eventually to final customers (figure 1, panel B). This shows that what looks like a chain of suppliers for a single firm is,

Figure 1. Supply Chain Perspectives: Business Value Chain versus Economic Input-Output Table



Source: Authors' elaboration of the Porter (1985) value chain (panel A) and a schematic view of a firm-level input-output table (panel B).

in fact, part of a matrix from the economy-wide perspective. In addition, the economic viewpoint introduces a distinction between primary inputs like labor and capital, intermediate inputs such as parts and components, and final goods.

One way to conceptualize the differences between the two methods is to consider the analogy to the differences between family trees that serve as a parallel to the business approach, and broader genealogical approaches such as social network analysis, which are akin to the economic approach. In the context of family trees, parents can be viewed as tier 1 suppliers, grandparents as tier 2 suppliers, and so forth. Although family trees provide a valuable means of identifying key familial connections, they are insufficient for grasping the complexities of broader communities. For a more comprehensive understanding, social network analysis is essential.

The business and economic approaches each have their advantages.[1] The business view allows much greater attention to detail as panel A in figure 1 makes clear. By focusing on a single firm, an analyst can delve deep into issues such as logistics, inventory control, and risk management strategies as well as the required administrative tasks ranging from financial planning to purchasing policies (horizontal bars in panel A). Additionally, they can concentrate on corporate relations, partnerships, contracting, and product portfolios. If the ultimate policy goal is to avoid disruption of production of a particular good, say, semiconductors, the business approach is the one to take. It is like following a river from its mouth back to the source of all its tributaries. This approach, however, would not have picked up the shock to US car production in 2020 that came when the demand for semiconductors boomed from other sectors, like work-from-home equipment. For that, an economy-wide perspective is necessary.

THE CORE DIFFICULTY AND THE TWO SOLUTIONS The two approaches, while quite different, face a common core difficulty: the massive complexity of modern supply chains. The business approach and the economic approach take very different paths in addressing this core difficulty. An illustration using the auto industry clarifies the two solutions, each of which involves ignoring certain aspects of the complexity.

The business approach example comes from Lund and others (2020). This study found that General Motors (GM) had 856 tier 1 suppliers, but these 856 suppliers had suppliers themselves, the so-called tier 2

1. At a conceptual level, the two perspectives can also be combined. For instance, drawing upon Feenstra (2009), Fort (2023) presents a framework for firm decisions to engage internationally and outsource tasks.

suppliers, as did the tier 2 suppliers, and so on. The research estimated that GM had a staggering 18,000 suppliers in tier 2 and below. Given that each of these 18,000 suppliers had its own roster of suppliers, an exhaustive cataloging of GM's suppliers would create a sequence that reaches what Buzz Lightyear would call "infinity and beyond."

The business approach keeps the complexity manageable by drawing the line at the number of tiers investigated. The economic approach takes a very different method to the Buzz Lightyear problem, a very different approach to the suppliers of the suppliers, and embraces a very different type of simplifying assumption. The key is an analytic tool called input-output (IO) analysis, which works at the level of sectors rather than firms. The payoff from this simplification—aggregating all firms into sectors—is that IO analysis can deal fully with the suppliers-of-suppliers challenge. We illustrate this with the US car industry.

WHERE US-MADE CARS ARE MADE: ECONOMIC APPROACH In the economic approach, there are three levels of answers to the question, "Where are Ford cars actually made?" The first level is the easiest: one obvious answer is Dearborn, Michigan. When a Ford rolls off the assembly line in Dearborn, Michigan, we can say that the car was made in Dearborn. This is true, but it is not the whole truth. The second level admits that the Dearborn plant buys car parts from other firms. Many of those parts are not made in Michigan, and many are not made in the United States. Some are made in Canada, so we can say that some of the Dearborn-made cars were actually made in Canada. This is also true, but still not the whole truth. The third level digs into the fact that all the parts makers also buy parts—some of which are not made locally. Canadian car-part makers, for example, may source parts from Germany.

The problem is that the third level involves the same sort of Buzz Lightyear never-ending sequence encountered by the business approach. Parts makers buy parts from other parts makers that buy parts from other parts makers, and so on without end. IO analysis tackles the infinite recursion problem with matrix algebra.

I.B. Measuring Supply Chain Exposure with IO Tables

IO analysis, developed by Nobel laureate Wassily Leontief in the 1950s, shows how production in each sector relies on inputs from all sectors.[2] The

2. See Baldwin, Freeman, and Theodorakopoulos (2022) for a fuller discussion of IO analysis.

international version we use in this paper, the 2021 release of Inter-Country Input Output (ICIO) tables by the Organisation for Economic Co-operation and Development (OECD), tracks all sectors in the sixty-five countries in the data along with a rest-of-world aggregate.[3] A limitation of IO analysis is that it is conducted at the level of sectors and nations, so we cannot disaggregate down to the product or firm level. Moreover, because the data sets require detailed mapping and harmonization of data from national, regional, and international sources for different countries and across many time periods, IO data typically exhibit a larger lag in availability than, say, standard data on direct trade flows. For instance, the ICIO tables are available from 1995 to 2018.[4] There are efforts underway to use "nowcasting" methods to project IO calculations for the most recent years (even without complete data), but these are experimental at this stage (Mourougane and others 2023). In our view, the starting date is not a major issue since the expansion of offshoring and the "new" globalization began in earnest in the 1990s (Baldwin 2016). The end date is also less constraining than one might initially think because the COVID-19 pandemic caused significant disruptions to the global manufacturing and distribution networks, which are now stabilizing.

The heart of our analysis is the IO table and the distinction between goods that are used as intermediate inputs into the production of other goods (business-to-business, or B2B sales) and final goods sold to end users (business-to-customer, or B2C sales). The sum of a sector's sales of intermediate and final goods is called gross production, to distinguish it from net production, which corresponds to the output of final goods. Roughly speaking, gross production is the sector's total business turnover, or value of total sales. To avoid confusion, it is important to keep in mind that a sector both buys and sells intermediates. In this paper, we focus on supply-side exposure and note that a single sector's supply chain dependency turns on its purchases of intermediates, not its sales of intermediates. We could also look at the dependency on the selling side and work out a sector's dependence on supply chains for its sales.[5]

3. OECD, "OECD Inter-Country Input-Output Database," https://www.oecd.org/sti/ind/inter-country-input-output-tables.htm.

4. These tables form the basis for the OECD's Trade in Value Added (TiVA) database. Note that a new version of the OECD ICIO data, which comprises additional countries and two additional years, was released after the time that the analysis for this paper was conducted.

5. See Baldwin, Freeman, and Theodorakopoulos (2022) for discussion and calculations.

The IO table also shows the inputs that each sector in each country buys from every other sector in every other country. As such, the IO table has as many columns as rows, with each representing a sector in a particular country. The numbers in the table's cells represent the direct, or "face value," purchases by the column sector of inputs from the row sector. For example, the column in the IO table corresponding to the US Vehicles sector lists all the sector's purchases from all other sectors in every country. Using the second-level logic, the US Vehicles sector's purchases of inputs from other US sectors would be considered as made in the United States.

As it turns out, we can use IO analysis to solve the Buzz Lightyear, infinite sequence problem. With a series of simple yet unenlightening calculations, we can transform the IO table into the so-called Leontief matrix (see online appendix II for a more precise explanation). The elements of the Leontief matrix provide the third-level answer, in other words, the full links between all sectors and all nations, fully accounting for the fact that suppliers themselves have suppliers. To give it a name, we call the full accounting links "look-through" exposure.

FACE VALUE VERSUS LOOK-THROUGH EXPOSURE A critical feature of the economic approach is the distinction it makes between the face value exposure of a supply chain and its look-through exposure. Face value exposure measures look at the proximate origin of intermediate inputs. This corresponds to the second-level answer mentioned above that takes the origin of purchased intermediates at face value. For example, if an automaker in the United States buys a component from Canada, the face value exposure of the component is only to Canada. By contrast, the look-through exposure takes account of the fact that the Canadian producer of the component surely purchased inputs from other nations. In other words, the look-through exposure pierces the veil of the supplier network of suppliers supplying suppliers to identify the comprehensive link between a purchasing sector in one nation and every supplying sector in every nation.

As we shall see below, there is a substantial difference between supply chain exposure to some economies—especially China—when the exposure is measured on a look-through basis versus a face value basis.

LIMITATIONS OF INPUT-OUTPUT ANALYSIS A significant limitation of IO analysis is its omission of elasticities and lack of consideration for substitutability. For instance, the US textile industry heavily relies on imported inputs, many of which either originate in China or are produced using materials from China. At first glance, one might infer that this US sector is susceptible to disruptions. However, it is important to note that numerous countries export textiles and apparel. Consequently, any supply chain disruptions can often be quickly mitigated by switching to alternative suppliers. Additionally, the relatively straightforward nature of these products makes switching suppliers in this sector easier than with more complex components, such as transmissions for trucks.[6]

Recent work, for example, by Moll, Schularick, and Zachmann (2023), also highlights how substitutability and agility can help prevent full-blown supply chain crises. Drawing lessons from Germany, they point to the role that the European market played in mitigating gas shortages after Russia curtailed its supply, beginning in 2021, thus preventing full-blown supply chain shutdowns. While there is evidence that elasticities of substitution at the micro level are known to be smaller than at the macro level (Houthakker 1955; Jones 2005; Oberfield and Raval 2021), readily available elasticities—especially for intermediates—would allow us to study the quantitative links between GSC disruptions and economic outcomes in a more meaningful manner. Goldberg and Reed (2023) make the related point that one would need information on all the elasticities of substitution at a highly disaggregated level to properly assess a product market's ability to withstand a given shock.

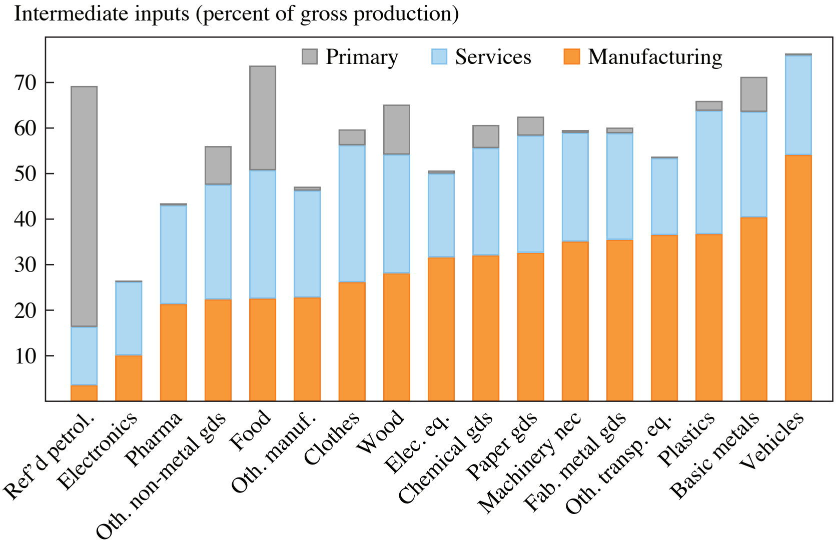
Furthermore, as mentioned above, an additional limitation of IO analysis is that it is conducted at the level of sectors and nations. Given the stringent requirements to construct IO tables, the data do not currently permit disaggregation down to the firm (or even detailed product) level, especially when multiple countries are included. As such, the economic repercussions of supply chain exposure, as it can be measured with the available IO data, may differ depending on the firm-level configuration of the supply chain (Baqaee and Farhi 2019; Elliott and Golub 2022).

II. The Links: Facts on United States and Comparator Nations

Some sectors, such as the auto sector, are inherently intensive in their use of purchased inputs and thus intrinsically more vulnerable to supply chain disruptions. To set the baseline for our study of foreign exposure, we look at the exposure of US manufacturing sectors to inputs from all sources, domestic and foreign, using the face value concept.

6. Antràs (2020) and Antràs and Chor (2022) note the sticky nature of supply chains and B2B relationships, which could in principle make it difficult to switch suppliers readily. However, some of the "stickiness" referred to is precisely generated by the lack of alternative suppliers, which is not the case for all sectors, as well as the need for complex, highly specialized parts and components, which are either not required or can more easily be replaced imperfectly for the production of some final goods.

Figure 2. Supply Chain Exposure of US Manufacturing Sectors by Type of Input, 2018



Source: Authors' elaboration based on 2021 OECD ICIO tables.
Note: The numbers shown represent the value of intermediates sourced by each US sector as a share of its total gross production.

II.A. Supply Chain Exposure of US Manufacturing Sectors

In the data upon which we draw—the 2021 release of the OECD ICIO tables[7]—we measure US purchased inputs in dollars and standardize each sector's input purchases by its gross production to allow comparisons across sectors and over time. Figure 2 presents the data for the year 2018, the most recent year in the data set. The chart displays stacked columns for each of the seventeen US manufacturing sectors identified in the database (see online appendix IV for a description of the products associated with various sectors).[8] The total height of each column reflects the importance

7. OECD, "OECD Inter-Country Input-Output Database," https://www.oecd.org/sti/ind/inter-country-input-output-tables.htm.

8. For convenience, we use shortened sector names as follows: Food products, beverages and tobacco = Food; Textiles, textile products, leather and footwear = Clothes; Wood and products of wood and cork = Wood; Paper products and printing = Paper gds; Coke and refined petroleum products = Ref'd petrol.; Chemical and chemical products = Chemical gds; Pharmaceuticals, medicinal chemical and botanical products = Pharma; Rubber and plastics products = Plastics; Other non-metallic mineral products = Oth. non-metal gds; Basic metals = Basic metals; Fabricated metal products = Fab. metal gds; Computer, electronic and optical equipment = Electronics; Electrical equipment = Elec. eq.; Machinery

of the sector's spending on intermediate inputs, counting inputs from all nations, including the United States itself. The bars within the columns indicate the broad source sectors of the intermediates. For clarity, we use the classic three-way classification of inputs, namely those coming from primary sectors (agriculture, mining, and utilities), services sectors, and manufacturing sectors. The sectors have been arranged in ascending order of their utilization of manufactured intermediate inputs.

For example, intermediate inputs amount to about 75 percent of the gross output of the Vehicles sector. How should we think about this 75 percent figure? Gross output in our data is measured in dollars and is defined as the sum of all costs, viewing profit as a payment to a factor of production and thus a cost. The costs comprise payments to factors of production (labor, capital, etc.) and purchased inputs (i.e., intermediate goods). The 75 percent figure means that, for the Vehicles sector, intermediate purchases make up three-quarters of all the costs. That is a very large number, and it means that the US Vehicles sector is highly exposed to supply chain issues—both domestic and foreign.

Note that intermediate inputs account for over half the costs in fourteen of the seventeen sectors. Even the sector with the lowest dependency, Electronics, has about 25 percent of its production cost linked to suppliers. Moreover, this 25 percent figure has to be handled with care since it is only for US manufacturers. At the global level, the Electronics sector is one of the most intensive users of intermediate goods, but the United States makes only a narrow range of the goods. Thus, the sector's low dependence shown in figure 2 arises from selection issues, not a ground-level reality of production processes. A similar point applies to the US pharmaceutical industry. In this sector, goods produced in the United States rely on intellectual property, which in the IO table and figure 2 registers as a service sector input.

Much of the recent discussion turns on manufactured inputs purchased by the manufacturing sector, so we zoom in on industrial inputs. Examining each sector's reliance on manufactured inputs, it is useful to divide the seventeen sectors into those with above- and below-median dependence on manufactured inputs. Notably, the sectors with above-median supply chain exposure include Electrical Equipment, Chemical Goods, Paper Goods,

and equipment, nec = Machinery nec; Motor vehicles, trailers and semi-trailers = Vehicles; Other transport equipment = Oth. transp. eq.; Manufacturing nec; Repair and installation of machinery and equipment = Oth. manuf.

Machinery nec (not elsewhere covered), Fabricated Metal Goods, Other Transport Equipment, Plastics, Basic Metals, and Vehicles. At the other end, the sectors that display below-median dependence are Refined Petroleum, Electronics, Pharmaceuticals, Other Non-Metal Goods (glass and ceramic products, construction materials, etc.), and Food.

Intermediate inputs originating from services sectors are also of interest. While usually seen as less vulnerable to shocks than industrial inputs, specific services such as cloud services, might pose significant risks for certain manufacturers. We have recently argued that trade in intermediate services is likely to dominate future trade (Baldwin, Freeman, and Theodorakopoulos 2023), but as of yet, they are not very important in the United States, so we set them aside for the rest of this paper.

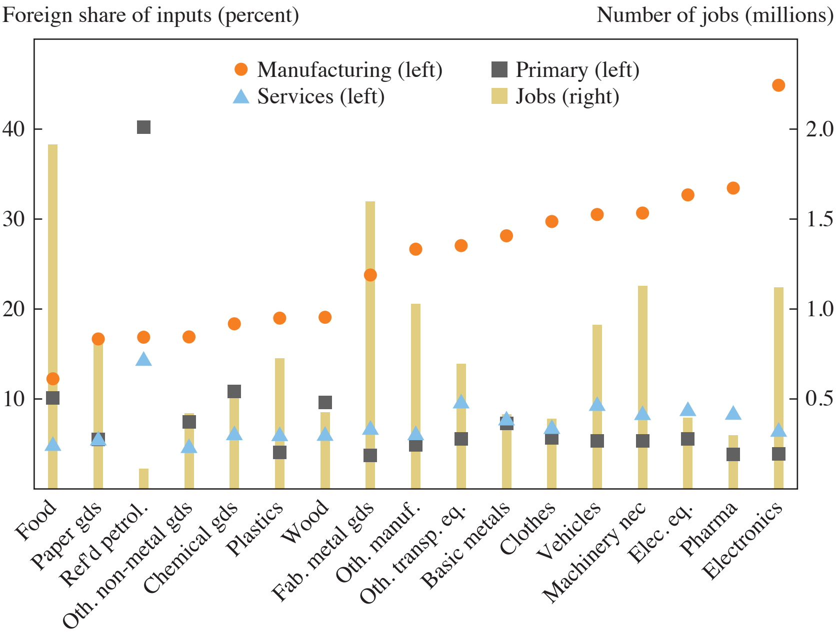
Regarding primary inputs, the observed patterns align with expectations. Primary inputs play a substantial role in only a handful of manufacturing sectors, including Refined Petroleum (53 percent), Food (23 percent), and Wood (11 percent). Surprisingly, the Basic Metals sector, known for producing items like steel girders, aluminum sheets, and copper wire, exhibits a relatively smaller share of inputs from primary sectors (8 percent). This can be attributed to the fact that, in the United States, much of the bulk production of basic metal goods relies on processing scrap metal rather than mining. As the collection and wholesaling of scrap metal are considered services, the US Basic Metals production depends less on primary sector inputs than one might assume.

II.B. Foreign Supply Chain Exposure by Sector at Face Value

Here we shift the focus to foreign sources of intermediate inputs—continuing to use the face value concept. Before looking at the facts, it is important to put the notion of foreign exposure into context to dispel the idea that foreign suppliers are somehow innately riskier than domestic suppliers. The point is that the riskiest thing to do with supply chains is to put all your eggs in one basket, even when the basket is at home (Miroudot 2020b; Baldwin and Freeman 2020a). Diversification of suppliers at home and abroad can be a useful buffer against shocks. During the pandemic, for example, having access to foreign suppliers was critical to reduce the disruption caused by domestic demand shocks in medical products (Evenett 2021). In short, the simplistic view that domestic suppliers are safe and foreign suppliers are risky is just that—simplistic.

Turning to the numbers, figure 3 unpacks the facts from figure 2 by displaying the foreign sourcing in each of its stacked bars. For example, manufacturing inputs for the rightmost column in figure 2 shows the share

Figure 3. Foreign Share of Intermediate Inputs by Type and Number of Jobs, United States, 2018



Source: Authors' elaboration based on 2021 OECD ICIO tables and OECD 2021 Trade in Employment (TiM) database.

Note: This figure shows the sector's foreign purchased inputs as a share of its total inputs (domestic and foreign) by type of input (left axis) and number of US jobs (right axis).

of industrial inputs in the cost of production in the Vehicles sector. The Vehicles point for manufactured inputs in figure 3 indicates that 31 percent of these inputs are sourced from abroad. The domestic share is naturally the balance between the foreign share and 100 percent.

The first thing to note is that the focus of the recent public debate on industrial inputs—as opposed to, for example, primary inputs—seems justified. Apart from Refined Petroleum, foreign exposure to inputs in the primary and tertiary sectors is rather limited; the foreign share for these types of goods is generally less than 10 percent. As such, the rest of this paper focuses exclusively on the role of manufactured inputs in supply chains. A second key fact that emerges from figure 3 is the similarity of the foreign exposure shares when it comes to manufactured inputs. Apart from Electronics, which has a very high foreign share (45 percent), and Food, which has a very low foreign share (12 percent), the US manufacturing sectors source between 16 percent and 33 percent of their manufactured inputs from abroad, with the median imported share being 27 percent. The foreign share is above the median for Other Transport Equipment, Basic Metals, Clothes, Vehicles, Machinery nec, Electrical Equipment, Pharmaceuticals, and Electronics. Nine of the seventeen sectors have foreign shares over a quarter.

The fact that the median foreign share is 27 percent means that most US sectors source the majority of their inputs from domestic suppliers. This is to be expected. As is true of all mega-economies, the United States is quite self-sufficient in industrial inputs (Baldwin and Freeman 2022). The explanation is straightforward. Empirical studies show that trade flows are very sensitive to distance; the rough rule of thumb is that bilateral trade flows fall by half when the distance between countries doubles (Head and Mayer 2014). Research also shows that the anti-trade effect—or to put it differently, the localization effect—of distance is even higher for intermediate goods (Miroudot, Lanz, and Ragoussis 2009; Conconi, Magerman, and Plaku 2020). The distance effect is countered by a size effect whereby countries trade more with big economies. It is natural, then, that the United States trades mostly with itself. It is, after all, a very large economy that is far from most nations, especially other large nations. Canada and Mexico are exceptions. Online appendix figure A1 shows this self-reliance in numbers. For the average US manufacturing sector, about 80 percent of all intermediates are sourced domestically. Thus, most of the United States' supply chain exposure is to itself.

When thinking about a sector's exposure to foreign suppliers and the implications that such exposure might have for the economy, a second set of important facts is the sector's size. Size, however, can be defined in many ways. Figure 3 shows the sectors' sizes as measured by jobs. The largest sector is Food, with almost 2 million employees in 2018. Fabricated Metal Goods is the second largest, with roughly 1.6 million jobs. Three other sectors employ more than a million people (Electronics, Other Manufacturing, and Machinery nec), but the rest of the sectors are comparatively small. Refined Petroleum, Pharmaceuticals, Clothes, Electrical Equipment, Basic Metals, Other Non-Metal Goods, and Wood all employ less than half a million workers.

II.C. Hidden Exposure: Look-Through versus Face Value Exposure

The next step is to look at exposure by sector and source nation, switching to the look-through basis to get the complete exposure of sectors to particular foreign suppliers. Our data set has sixty-five economies, but to concentrate on the most important, we show the figures for only the top fifteen suppliers, which account for the lion's share of imported intermediates.

Figure 4 presents figures for the value of industrial inputs on a look-through basis, with the values standardized by the value of each sector's total purchases of manufactured intermediates from all sources—domestic and foreign. The supplying economies are listed in descending order of importance as a source, as measured by the simple average of the corresponding country's share in each of the seventeen manufacturing sectors (see rightmost column). To interpret the figures, note that, for example, the 5.1 percent in the Vehicles column for the China row indicates that China is the source of 5.1 percent of all manufactured inputs used by the US Vehicles sector on a look-through basis.

China's role as the dominant foreign supplier of industrial inputs to US manufacturing sectors is clear. Looking at the simple average across the seventeen sectors (rightmost column) shows a figure of 3.5 percent for China—close to three times larger than the average for the next closest supplier, Canada. Indeed, China's average share is more than the sum of the three next most important suppliers combined. In seven of the seventeen sectors, including Electrical Equipment, Plastics, and Fabricated Metal Goods, China is a more important supplier than the next four suppliers combined. In four of those sectors, China's share exceeds that of the next five most important suppliers. In two of these sectors, Clothes and Electronics, China's share exceeds that of the other top ten suppliers. This reflects the fact that China is also the top supplier for most of the United States' other top suppliers (Baldwin, Freeman, and Theodorakopoulos 2022).

Canada is particularly important as a supplier in Vehicles, Basic Metals, and Fabricated Metal Goods. Mexico is the third most important supplier followed by Japan, Germany, and South Korea. Once we get beyond the top six supplying economies, the only large suppliers are Ireland and Switzerland in the Pharmaceuticals sector (each accounting for more than 1 percent of inputs).

Our look-through measure also tells us that it is not just the United States that is heavily dependent on China for industrial supplies. Baldwin, Freeman, and Theodorakopoulos (2022), for example, show that in addition to the United States, all other major manufacturing nations source at least 2 percent of their total industrial intermediates from China.[9]

9. The nations included are Canada, Mexico, Germany, the United Kingdom, France, Italy, Japan, South Korea, and India.

Figure 4. Look-Through Exposure to Foreign Manufactured Intermediates (Percent), 2018

	Vehicles	Machinery nec	Basic metals	Elec. eq.	Oth. transp. eq.	Clothes	Fab. metal gds	Plastics	Oth. manuf.	Wood	Chemical gds	Pharma	Paper gds	Electronics	Oth. non-metal gds	Food	Ref'd petrol.	Manuf. avg.
China	5.1	4.9	2.9	5.5	4.6	6.3	3.1	3.4	3.8	3.2	2.7	1.4	3.1	4.4	2.6	1.9	1.2	3.5
Canada	2.1	1.4	2.6	1.5	1.2	.6	1.8	1	1	1.6	.9	.4	1.3	.3	.7	.9	1	1.2
Mexico	3.4	1.8	1.7	1.6	1.3	.6	1.3	.7	.9	.7	.6	.2	.7	.8	.6	.6	.4	1.1
Japan	2.6	1.4	.8	.9	1.3	.5	.7	.7	.6	.5	.7	.3	.5	.5	.4	.4	.3	.8
Germany	1.5	1.1	.9	.7	.9	.4	.7	.7	.5	.5	.7	.8	.5	.3	.4	.4	.3	.7
South Korea	1.4	.9	.7	.8	.8	.5	.7	.6	.5	.4	.5	.2	.5	.6	.3	.3	.2	.6
India	.4	.3	.3	.2	.2	.8	.3	.4	.4	.3	.3	.5	.3	.1	.2	.2	.1	.3
Taiwan	.5	.4	.4	.4	.5	.3	.4	.3	.3	.2	.3	.1	.2	.4	.2	.2	.1	.3
Italy	.5	.5	.4	.3	.4	.3	.3	.2	.2	.2	.2	.3	.2	.1	.2	.2	.1	.3
Brazil	.3	.3	.7	.3	.4	.1	.5	.2	.2	.3	.2	.1	.3	.1	.2	.2	.2	.3
Ireland	.1	.1	.1	.1	.1	.2	.1	.4	.1	.1	.4	2	.2	.1	.1	.1	.1	.3
France	.2	.2	.2	.2	.9	.2	.2	.3	.2	.2	.3	.2	.2	.1	.1	.1	.1	.2
Russia	.2	.3	.6	.3	.2	.1	.5	.2	.2	.2	.2	.1	.1	.1	.1	.1	.2	.2
UK	.4	.2	.1	.1	.4	.1	.1	.2	.1	.1	.2	.3	.1	.1	.1	.1	.1	.2
Switzerland	.1	.2	.1	.1	.2	.1	.1	.1	.1	.1	.1	1.2	.1	.1	.1	.1	0	.2
RoW	3.1	2.8	3.7	2.9	2.7	2.6	2.9	2.3	2.1	2	2	2	1.9	1.5	1.5	2	1.3	2.3
Foreign	21.9	16.8	16.2	16.1	16	13.8	13.7	11.5	11.2	10.3	10.3	10.1	10.1	9.5	8	7.7	5.9	12.3
USA	78.1	83.2	83.8	83.9	84	86.2	86.3	88.5	88.8	89.7	89.7	89.9	89.9	90.5	92	92.3	94.1	87.7

Source: Authors' elaboration based on 2021 OECD ICIO tables.

Note: Look-through exposure is the foreign production exposure: import side (FPEM) indicator as described in Baldwin, Freeman, and Theodorakopoulos (2022) and is computed as the share of manufactured inputs sourced by a given US sector from a given country on a look-through basis in total manufactured intermediates across all sources (foreign and domestic) on a look-through basis. "RoW" stands for the rest of the world. "Foreign" is the sum of all foreign sources.

To highlight the hidden exposure in US supply chains, figure 5 presents the percentage point difference between look-through exposure in figure 4, and the equivalent numbers for face value exposure.[10] The biggest differences are in sectors that are marked by extensive global supply chains. In such sectors, the hidden value gets added at many stages of the globalized production process. The differences are particularly marked in Vehicles, Machinery nec, Electrical Equipment, and Clothes. As far as source nations are concerned, the biggest hidden value is for nations that are important producers of intermediate goods and extensively involved in global supply chains. This includes the major manufacturing nations, which are (apart from the United States) China, Germany, and Japan.

The hidden exposure is very large. For example, the Vehicles sector's exposure to Chinese industrial inputs is about four times higher than indicated by the face value measure. In fact, the Chinese look-through exposure is more than four times the face value exposure in eight of the seventeen sectors. The percentage point differences are, on average, still quite high for Canada, Mexico, Japan, Germany, and South Korea, as the rightmost column shows. The only other big hidden exposure numbers are for Ireland and Switzerland in Pharmaceuticals.

II.D. Hidden Exposure Take 2: Rapid Concentration of Foreign Sourcing

The "hidden" in hidden exposure in the previous section referred to the sourcing of intermediate inputs that was masked behind the Buzz Lightyear spiral of inputs used to make inputs. Here we turn the spotlight on another form of hidden exposure, namely the rapid geographic concentration of supply chain exposure.[11] It could be considered as hidden in the sense that it may have been underappreciated since it happened so fast.

CONCENTRATED SOURCING FROM CHINA The manufacturing of intermediates has rapidly become geographically concentrated in China. China's ascent as the world's top manufacturer is well documented (World Bank 2020). Less well-known is the fact that its production of intermediate manufactured goods has advanced even more rapidly than its production of final goods. Simply put, China has become what might be called the "OPEC of industrial inputs" (Baldwin 2022, par. 15). This concentration matters since supply chains fundamentally revolve around intermediate goods.

10. See online appendix figure A1 for the face value equivalent to figure 4.

11. In our analysis, we focus on concentration at the country level. However, it is worth noting that concentration can also exist within a given country. Data on the latter are typically not readily available at large scale.

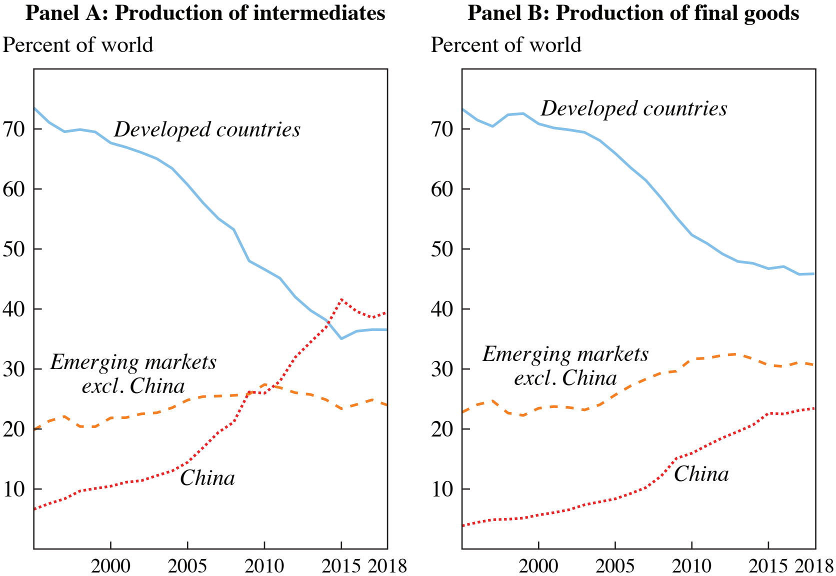
Figure 5. Hidden Exposure of US Sectors to Foreign Manufactured Intermediates (Percentage Point Difference between Look-Through and Face Value Exposure), 2018

	Vehicles	Machinery nec	Basic metals	Elec. eq.	Oth. transp. eq.	Clothes	Fab. metal gds	Plastics	Oth. manuf.	Wood	Chemical gds	Pharma	Paper gds	Electronics	Oth. non-metal gds	Food	Ref'd petrol.	Manuf. avg.
China	3.9	3.5	2.2	3.7	3.4	4.2	2.3	2.4	2.6	2.4	2	1	2.3	2.8	1.8	1.6	1.2	2.5
Canada	1	.7	1.1	.6	.6	.3	.9	.5	.5	.7	.4	.2	.6	.2	.4	.5	.9	.6
Mexico	1.4	.7	.7	.6	.6	.3	.6	.4	.4	.4	.3	.1	.4	.2	.3	.4	.4	.5
Japan	1.7	.9	.6	.6	.8	.3	.5	.5	.4	.4	.4	.2	.4	.3	.3	.3	.3	.5
Germany	.9	.6	.5	.4	.6	.3	.5	.4	.3	.3	.4	.4	.3	.2	.3	.3	.3	.4
South Korea	1	.6	.5	.5	.6	.4	.5	.4	.3	.3	.3	.2	.3	.4	.3	.3	.2	.4
India	.2	.2	.2	.2	.1	.4	.2	.2	.2	.2	.2	.2	.2	.1	.1	.2	.1	.2
Taiwan	.3	.3	.2	.3	.3	.2	.3	.2	.2	.2	.2	.1	.2	.3	.1	.1	.1	.2
Italy	.3	.3	.2	.2	.3	.2	.2	.2	.1	.1	.2	.2	.1	.1	.1	.1	.1	.2
Brazil	.2	.2	.4	.2	.2	.1	.3	.1	.1	.2	.1	0	.2	0	.1	.1	.2	.2
Ireland	.1	.1	.1	.1	0	.1	.1	.2	.1	.1	.2	.4	.1	0	.1	.1	.1	.1
France	.2	.1	.2	.1	.4	.1	.1	.2	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
Russia	.2	.2	.4	.2	.1	.1	.3	.1	.1	.1	.1	0	.1	0	.1	.1	.1	.1
UK	.2	.1	.1	.1	.2	.1	.1	.1	.1	.1	.1	.1	.1	0	.1	.1	.1	.1
Switzerland	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.5	.1	.1	0	0	0	.1
RoW	2.2	1.8	2.2	1.7	1.7	1.4	1.8	1.4	1.3	1.3	1.3	1	1.3	.9	1	1.4	1.2	1.4
Foreign	13.7	10.3	9.6	9.4	10	8.5	8.5	7.3	6.8	6.8	6.4	4.7	6.6	5.7	5.3	5.8	5.4	7.7
USA	10.3	7.4	9.2	6.3	7.2	6.4	8.3	8.6	5.9	8.5	7.9	4.1	8.5	2.2	6.4	10.2	5.8	7.2

Source: Authors' elaboration based on 2021 OECD ICIO tables.

Note: This figure presents the percentage point difference between the look-through exposure (figure 4) and face value exposure (online appendix figure A1). "RoW" stands for the rest of the world. "Foreign" is the sum of all foreign sources.

Figure 6. World Production of Intermediate and Final Manufactured Goods, 1995–2018



Source: Authors' elaboration based on 2021 OECD ICIO tables.
Note: "Developed countries" include the European Union (EU), European Free Trade Association (EFTA) nations, the United Kingdom, the United States, Canada, Japan, Australia, and New Zealand. "Emerging markets excl. China" includes all other nations (including the rest of world aggregate) except China.

As figure 6 (panel A) shows, as recently as 1995, more than 70 percent of all intermediate goods were made in developed countries. At the time, the largest single producer—the United States—accounted for about 20 percentage points of the 70 percent figure. By the 2010s, China's production of intermediate goods surpassed one-quarter of the whole world's production—a figure that is almost twice as large as the next most important supplier (the United States). In 2018, China's manufacturing sector produced a greater value of intermediates than all developed countries combined.

China's rise as a powerhouse of manufactured intermediates production was also rather sudden. At its peak in 2015, China accounted for 42 percent of world manufactured intermediates production, but just ten years earlier, the figure was 14 percent. As shown, the rapid rise has attenuated, and appears to have plateaued, but at a level that implies an astonishing geographic concentration at the world level.

Panel B shows that China's share of global final goods production has been less rapid and less impressive. China's share of world production of final goods and services has also risen compared to 1995 values—seemingly at the expense of developed country production—and is now close to the levels for all other emerging markets. It is, however, still more than 20 percentage points below the collective share of developed nations.

GEOGRAPHIC CONCENTRATION BY SECTOR AND SOURCE NATION China's rise as the premier foreign provider to US supply chains necessarily reduced the relative importance of other suppliers. Further insight into the concentration of US sourcing can be had by looking at the percentage point changes in the shares between 1995 and 2018 by sector and by source nation. Since we are interested in the full impact of the changes, we work with the look-through concept that takes account of all the inputs to the inputs.

Figure 7 displays the numbers, where darker shades of positive numbers indicate higher exposure and darker shades of negative numbers indicate lower exposure in 2018 versus 1995. As in the previous heat maps, it includes the US sourcing from itself. As noted above, the United States, as is true of all mega-economies, supplies most of its own intermediates (as can be seen in the bottom row of figure 4). Figure 7 shows that this self-supplying has diminished. All the entries in the bottom row (the change in the US share of industrial inputs to itself) are negative except for the Electronics sector. The average percentage point (pp) drop across the sectors is 3.4 pp, with the figure ranging from +4.2 pp for the Electronics sector to –7.5 pp in the Vehicles sector. The Pharmaceuticals sector is another standout with a drop of 6.2 pp. The drop in domestic sourcing is matched by an increase in foreign sourcing.

The change in the share provided by all foreign nations is in the next to last row, and these numbers are all positive except in the Electronics column. The most remarkable feature of these numbers is the fact that, apart from Mexico, a large share of the row entries for all the other major suppliers are negative. The simple averages of the changes are only positive for China, Mexico, South Korea, India, Ireland, and Switzerland. China's average change is 3.2 pp, which is far greater than those of the others to which the United States has become more exposed.

It is notable that China's average share rise is only slightly less than the average share drop in US domestic sourcing. In some of the most supply chain-exposed sectors, like Other Transport Equipment and Electrical Equipment, China's percentage point gain is similar to the United States' percentage point drop. The data cannot shed light on how this change occurred, for example, due to offshoring of US intermediate goods

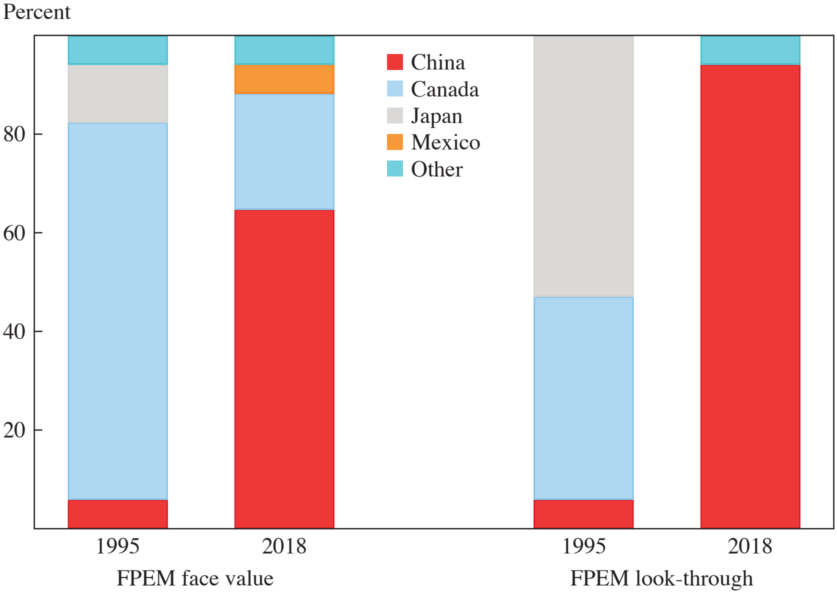
Figure 7. US Look-Through Exposure by Sector (Percentage Point Differences), 1995 versus 2018

	Vehicles	Machinery nec	Basic metals	Elec. eq.	Oth. transp. eq.	Clothes	Fab. metal gds	Plastics	Oth. manuf.	Wood	Chemical gds	Pharma	Paper gds	Electronics	Oth. non-metal gds	Food	Ref'd petrol.	Manuf. avg.
China	4.7	4.6	2.6	5.1	4.3	5.1	2.8	3	3.4	2.9	2.4	1.3	2.8	3.8	2.3	1.7	1.1	3.2
Canada	–.7	–.2	.5	–.1	–.4	–.1	.2	–.2	–.5	–1	–.2	0	–1	–.7	–.3	–.2	.1	–.3
Mexico	2.2	1.1	1.2	.9	.8	.2	.9	.4	.5	.3	.4	.1	.4	–.2	.3	.4	.2	.6
Japan	–1.4	–1.2	–1.2	–1.2	–1.1	–.4	–1	–.7	–.7	–.5	–.7	–.2	–.4	–3.2	–.5	–.4	–.3	–.9
Germany	.4	.1	0	0	0	0	0	0	0	.1	–.1	.4	.1	–.2	0	0	0	0
South Korea	.8	.5	.3	.4	.3	–.1	.3	.3	.1	.2	.3	.2	.3	–.7	.2	.2	.1	.2
India	.3	.2	.2	.2	.1	.7	.2	.3	.3	.2	.2	.4	.2	0	.2	.2	.1	.2
Taiwan	–.1	–.1	0	–.1	–.2	–.3	0	–.1	–.1	–.1	0	0	0	–.8	–.1	–.1	0	–.1
Italy	.2	.1	.1	0	.1	–.2	.1	0	–.1	0	0	0	0	–.1	–.1	0	0	0
Brazil	0	0	.1	0	.2	–.1	0	0	0	.1	.1	0	.1	–.1	0	0	.1	0
Ireland	.1	.1	.1	.1	0	.2	.1	.3	.1	.1	.3	1.9	.1	0	.1	.1	.1	.2
France	–.1	–.1	–.2	–.1	0	0	–.1	0	–.1	0	–.1	0	0	–.2	–.1	0	0	–.1
Russia	0	0	–.1	–.1	0	0	0	0	0	0	0	0	0	–.1	.1	0	.1	0
UK	0	–.2	–.2	–.2	–.9	–.1	–.2	–.2	–.1	–.1	–.2	0	–.1	–.3	–.1	–.1	–.2	–.2
Switzerland	0	0	0	0	.1	0	0	0	0	0	0	.7	0	0	0	0	0	.1
RoW	1	.7	.5	.5	.5	.3	.4	.5	.3	.4	.2	1.2	.7	–1.4	.1	.4	0	.4
Foreign	7.5	5.6	3.9	5.3	3.8	5.4	3.5	3.7	3	2.5	2.9	6.2	3.3	–4.2	2	2.2	1.2	3.4
USA	–7.5	–5.6	–3.9	–5.3	–3.8	–5.4	–3.5	–3.7	–3	–2.5	–2.9	–6.2	–3.3	4.2	–2	–2.2	–1.2	–3.4

Source: Authors' elaboration based on 2021 OECD ICIO tables.

Note: This figure presents the percentage point difference between look-through exposure in 2018 and look-through exposure in 1995. Look-through exposure is the foreign production exposure: import side (FPEM) indicator as described in Baldwin, Freeman, and Theodorakopoulos (2022) and is computed as the share of manufactured inputs sourced by a given US sector from a given country on a look-through basis in total manufactured intermediates across all sources (foreign and domestic) on a look-through basis. "RoW" stands for the rest of the world. "Foreign" is the sum of all foreign sources.

Figure 8. Top Foreign Supplier of Industrial Inputs to US Manufacturing Sectors, 1995 versus 2018, Face Value versus Look-Through



Source: Authors' elaboration based on 2021 OECD ICIO tables.
Note: This figure shows the share of US manufacturing sectors for which the top supplier is China, Canada, Japan, Mexico, or other. "FPEM" stands for foreign production exposure: import side (Baldwin, Freeman, and Theodorakopoulos 2022).

production to China, US deindustrialization, or Chinese industrialization. In other sectors, such as Vehicles, the US decline is significantly greater than the Chinese rise since the supply chain also spread to other foreign suppliers. In the Vehicles sector, we see a moderate decline in Canada's and Japan's shares, a big decline in the United States' share, and an important rise in the shares of Mexico, South Korea, and, of course, China.

THE TOP FOREIGN SUPPLIER OF INDUSTRIAL INPUTS OVER TIME The two forms of what we are calling hidden exposure—the look-through versus face value measures on the one hand, and the rapid geographic concentration of sources on the other—can be usefully compared and contrasted by examining the nationality of the top supplier to each of the United States' seventeen manufacturing sectors. Figure 8 shows the share of the seventeen sectors where the top supplier is China, Canada, Mexico, Japan, or some other nation. The chart also shows how this statistic changed from the beginning of our data, 1995, to the end, 2018. The two left-hand columns use the face value concept to examine the United States' top supplier in 1995 and 2018, while the right-hand columns use the look-through concept in 1995 and 2018.

When it comes to our second form of hidden exposure, the main takeaway from the chart is that China's role as the top supplier spreads rapidly. Turning first to the leftmost pair of stacked columns, we see that in 1995, which was when the new offshoring-oriented globalization was just starting (Baldwin 2006, 2016), China was the top industrial input supplier to about 5 percent of US manufacturing sectors. By 2018, the share was over 60 percent. The change is even starker when using the look-through measure (rightmost pair of stacked columns). China has shifted from being the top supplier in about 5 percent of the sectors to the top supplier in all but one sector (Pharmaceuticals).

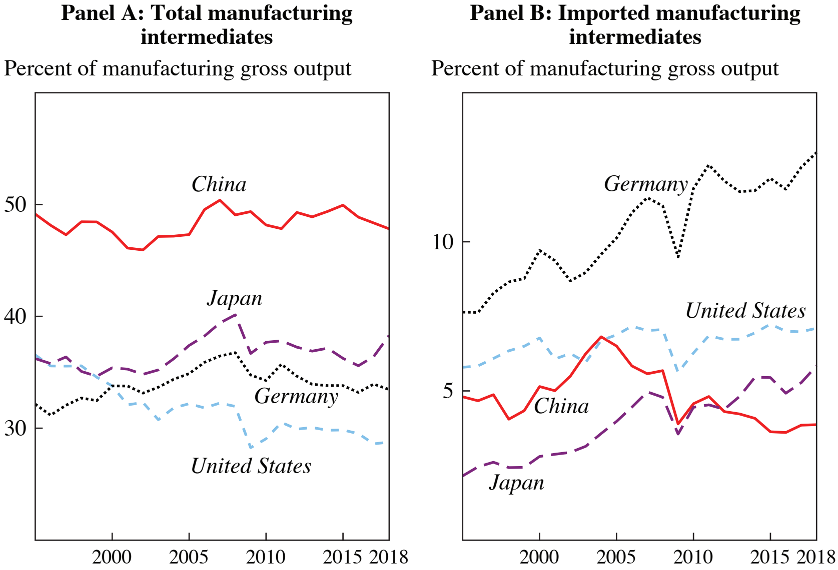
The chart also shows a different take on our first aspect of hidden exposure. Comparing the two stacked columns for 2018 (the second and fourth columns), we see that while China is clearly dominant using the face value concept, it is much more so on a look-through basis.

The chart also illustrates the fact that Japan was, in 1995, playing a similar role to the one that China is playing today. In 1995, the US exposure to foreign industrial inputs was much lower overall since back then the globalization of industrial supply chains was just starting. Most supply chains were domestic. Sticking with the look-through concept to take account of the direct in addition to all indirect sourcing, we see that among the foreign suppliers, Japan had the most top spots. Japan's role, however, looks much less dominant when viewed from the face value perspective. Comparing the first stacked column (1995, face value) to the third stacked column (1995, look-through), we see that the hidden exposure was to Japan back then, not China. This was due to the fact that while the United States was sourcing heavily from Canada, Canada was sourcing heavily from Japan. This was to be expected because Japan was one of the largest producers of intermediate goods outside of the United States.

II.E. Comparison with China

The facts for China could hardly be more different than those for the United States and the two other major manufacturing countries, Germany and Japan. China's industrialization is quite recent compared to that of the United States and other advanced economies, and its development journey was quite different. China started its industrialization with processing trade, which involved limited transformation of imported intermediate goods. From there, China built out its industrial base by producing domestically

Figure 9. Major Manufacturers' Exposure to Supply Chains, 1995–2018



Source: Authors' calculations based on OECD 2021 ICIO tables.

many inputs that had previously been imported. This task was facilitated by its massive and fast-growing internal market and government policy (Cui 2007), foreign investment, and transfers of foreign know-how (Wen 2016). The result is plain to see in figure 9, which also presents the figures for the United States, Japan, and Germany.

Panel A shows the nations' total usage of manufactured intermediates as a share of their manufacturing gross output. We see that Chinese industry is far more exposed to supply chains—taking domestic and international exposure together—than the other three giants. The share of China's manufacturing gross output that is made up of intermediate inputs is about 50 percent, and this figure has been fairly steady since 1995. The corresponding share for the other nations shown is much lower. Panel B, however, shows that Chinese industry is now less exposed to foreign intermediates than the other manufacturing giants. Specifically, China's foreign exposure started in the middle of the pack and rose sharply up to 2005 but has been falling rapidly since. It is now substantially lower in 2018 than that of the others. The United States' exposure to imported manufacturing intermediates is roughly twice, and Germany's is roughly three times that of China.

It is worth noting that all of these "Giant-4" economies are quite self-reliant when it comes to intermediate inputs. The most exposed is Germany, but even there, Germany sources over 85 percent of all its manufacturing intermediates from itself.

Relating this back to figures 4 and 5, we compute that China's average manufacturing look-through exposure to the United States is 0.6 percent (compared to the United States' average manufacturing look-through exposure on China, which is 3.5 percent).[12] And China's average manufacturing hidden exposure to the United States is 0.4, compared to the United States' average manufacturing hidden exposure to China, which is 2.5. Simply put, these counterpart measures underscore that China is much less reliant on US manufacturing than the US manufacturing is on Chinese production.

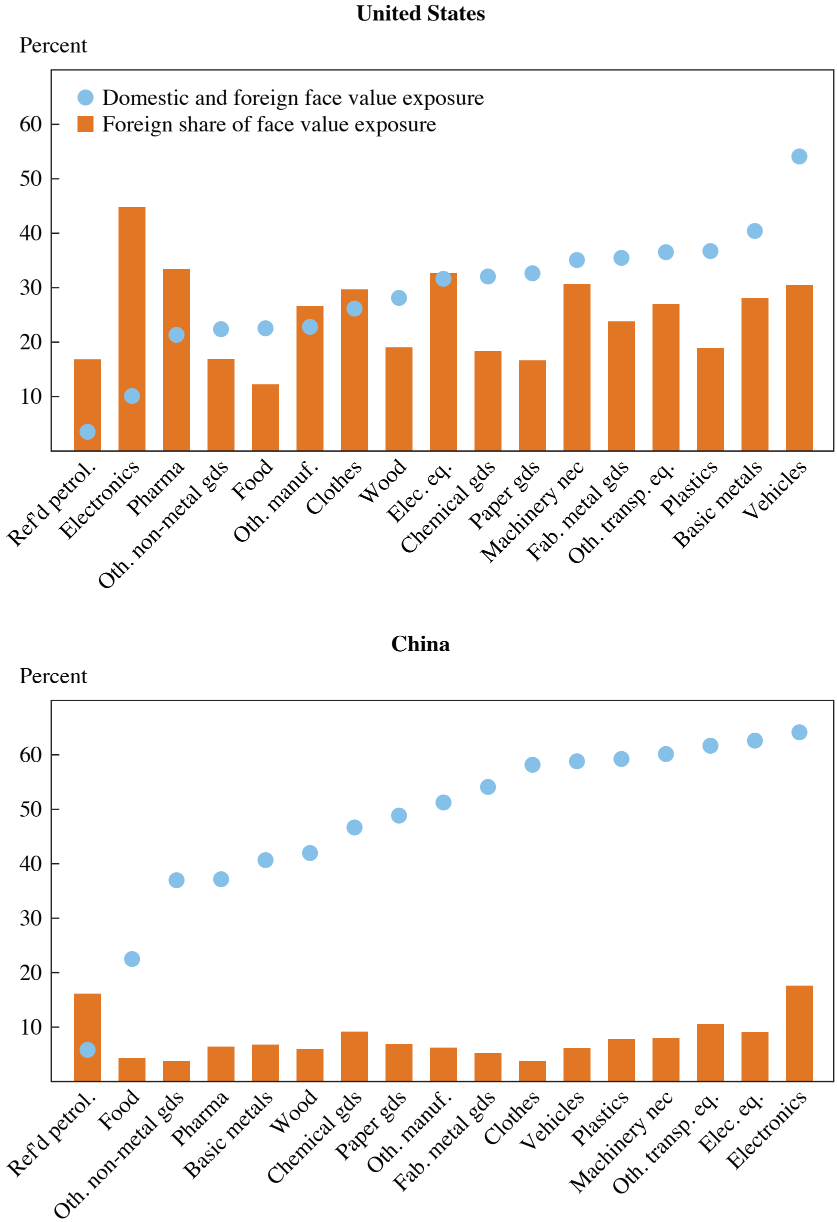
Looking closer, figure 10 shows that China's sectors are generally more exposed overall to supply chains (i.e., combining domestic and foreign sources) but much less exposed to foreign suppliers. For instance, China's foreign exposure is below 20 percent for all sectors, while for the United States, it is much higher, approaching 30 percent to 45 percent in some cases. The opposite holds for the overall (domestic plus foreign) exposure, which is much higher for China than it is for the United States in every single sector.

In terms of geographic concentration, China is also quite different than the United States, as figure 11 shows. This chart, which is comparable to figure 8, shows that China's foreign sourcing is not as concentrated as that of the United States. For instance, the far-right column shows that China's top supplier on a look-through basis is South Korea, but South Korea is the top supplier in only about 60 percent of Chinese manufacturing sectors. Japan, the United States, and other nations play a significant role as top suppliers. On a face value basis (second column from the left), Chinese foreign sourcing is even more diversified.

When it comes to rapid changes in geographic concentration, we do see big upward shifts in South Korea's role from 1995 to 2018, but it is not as stark as the shift that the United States experienced (figure 8). It is also interesting to note that the big hidden exposure for China in 1995 was to Japanese suppliers. On a face value basis (leftmost column), Japan's role was much lower than it was on a look-through basis.

12. Moreover, China's look-through exposure to all nations is comparatively low. Its highest average manufacturing look-through exposure is 1.1 percent with South Korea, which is substantially lower than all other nations' look-through exposure to China.

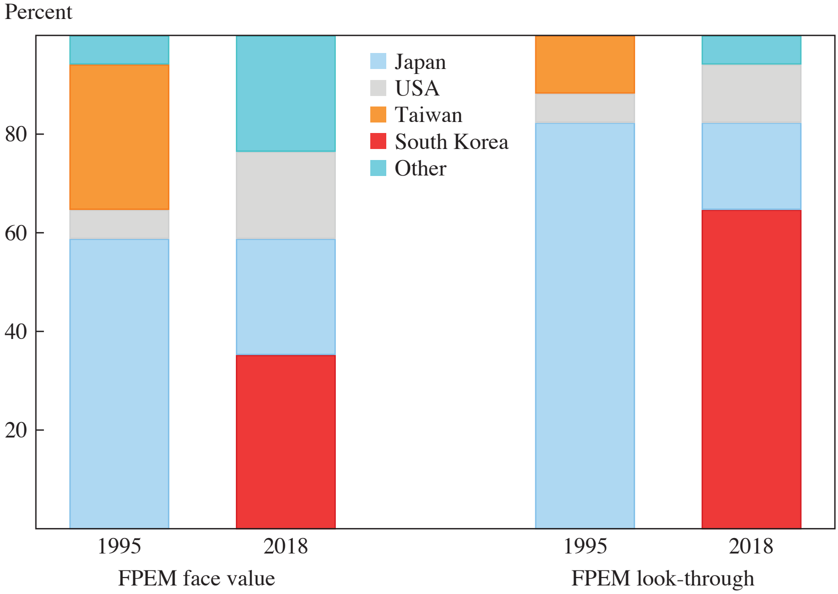
Figure 10. Overall and Foreign Supply Chain Exposure, United States versus China, 2018



Source: Authors' calculations based on OECD 2021 ICIO tables.

Note: This figure shows total (i.e., domestic and foreign) and imported (i.e., foreign) manufacturing intermediate inputs on a face value basis (as a percentage of a sector's gross output). The dots in the United States panel are repeated from figure 2.

Figure 11. Top Foreign Supplier of Industrial Inputs to Chinese Manufacturing Sectors, 1995 versus 2018



Source: Authors' elaboration based on 2021 OECD ICIO tables.
Note: This figure shows the share of Chinese manufacturing sectors for which the top supplier is Japan, South Korea, the United States, Taiwan, or other. "FPEM" stands for foreign production exposure: import side (Baldwin, Freeman, and Theodorakopoulos 2022).

II.F. Measuring Geographic Concentration with Standard Trade Data

The great advantages of IO analysis are the ability to distinguish face value trade from look-through trade and the ability to distinguish between outputs that are used as intermediate goods and those used as final goods. As intermediate goods are what supply chains are set up to acquire, this distinction is critical. The disadvantage that comes with IO analysis is the lack of detail that stems from the very extensive information necessary to estimate the underlying tables, especially at the world level, as opposed to a single-country level.

The sorts of supply chain disruptions that have attracted the attention of heads of state around the world—like those in the semiconductor and medical supply sectors—often involve very specific products. Thus, trade data serve as a valuable complement to the IO analysis since they are available at a much more disaggregated level. The US Census Bureau publishes export and import statistics at the ten-digit level following the

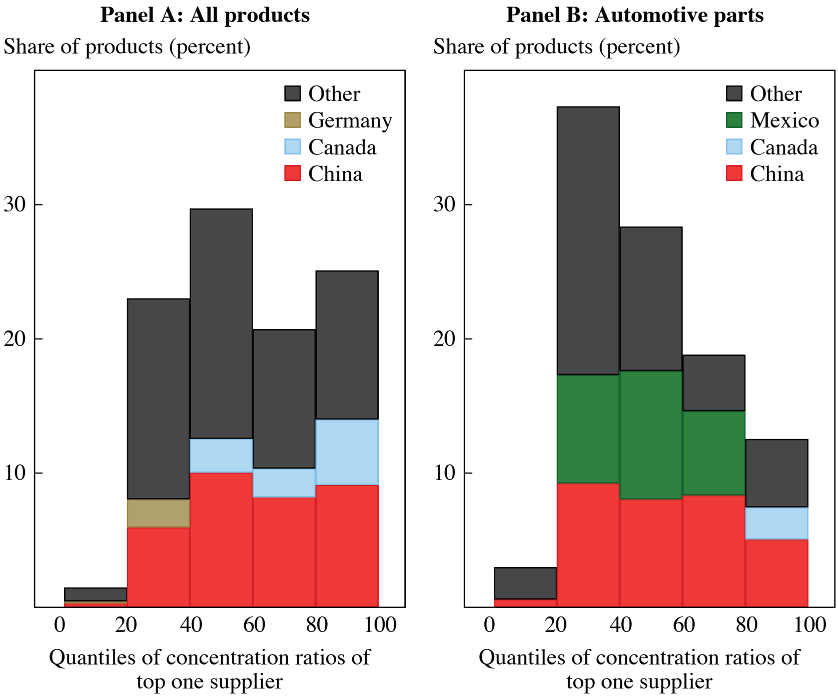
US Harmonized Tariff Schedule (HTS), which distinguishes more than 18,000 different products. To look at the supply chain vulnerability issue from a different perspective, we next turn to the HTS ten-digit data and look for concentration among source nations.

A couple of limitations of the ten-digit data are important to be kept in mind when thinking about the results we will present. The first is that we know neither which sector is importing the goods nor whether they are intermediate or final products. That is, we only know the type of good that is imported into the United States, but we cannot connect the import to a particular purchasing sector. There are some types of imports, like those associated with motor vehicles, where the HTS ten-digit product descriptions allow economists to identify which are intermediate inputs and which are final goods. Moreover, it is reasonable to assume that it is the US auto sector that is purchasing the intermediates. For instance, the product codes 8708305020 for brake drums and 7009100000 for rear-view mirrors are two clear examples. There are other types of imports, such as industrial chemicals, that could be used as inputs in a number of sectors. For these types of imports, we cannot associate geographic concentration with supply chain exposure of a particular sector. As a fallback, we take the exposure as that of the US manufacturing economy as a whole. The second limitation (beyond not always being sure if a product is an intermediate versus final good) is that the trade data only show the face value exposure. For example, if a car part is imported from Canada, we cannot know how much of the good was actually made in Canada and how much was made in another country.

With these caveats in mind, we turn to using the HTS ten-digit trade data to illustrate the geographic concentration of import sourcing. What we look at is the concentration of import sourcing for the 18,043 products that the United States imported in 2018, focusing on imports from a single nation.[13] This is shown in panel A of figure 12; the far-right bar indicates that for about a quarter of all imported products, 80 percent or more of the value came from a single source nation. The bars within the column show the frequency with which the single source supplier is China, Canada, Germany, or some other country. In about a third of the products in this top quintile, the single supplier is China. The other stacked columns in the

13. In line with our concentration analysis with IO data, we focus our attention on a single supplier at the product level. In the absence of firm-level data, we believe that this concentration level reveals particularly high exposure, especially to systemic shocks, which have a broad geographical reach.

Figure 12. Shares of Products Imported by the United States from a Single Source Nation by Quintile of Import Shares, 2018



Source: Authors' elaboration on US Census Bureau trade statistics.
Note: Panel A shows the quintile distribution of all 18,043 products (intermediate and final) imported by the United States in 2018; panel B shows the quintile distribution of all 335 automotive parts (intermediates only) imported by the United States in 2018.

chart are similar, but the bar heights represent goods where the top supplier provides 60–80 percent, 40–60 percent, 20–40 percent, and 0–20 percent of all imports, respectively. Thus, each of the 18,043 products is represented in only one of the five stacked columns.

The first salient fact that emerges from the chart is the remarkable geographic concentration of US imports. The leftmost column indicates that the top supplier was providing less than 20 percent of the total import value for less than 5 percent of the 18,043 products. Considering the two rightmost columns together shows that for almost half the products, more than 60 percent of the import value came from a single supplying nation. In short, the chart indicates a remarkably high level of geographic concentration of import sourcing.

A second noteworthy fact concerns the role of China. In the most concentrated products, for example those underlying the three rightmost columns, China is by far the most important supplier. However, a subtler aspect of this emerges when comparing China's role as a top supplier in figures 8 and 4. We saw in figure 4 that on a look-through basis, China was by far the top supplier in almost every sector. Its dominance is so great that its share of imported inputs was frequently greater than the sum of the next three largest suppliers combined. Yet, panel A in figure 12 would suggest that China is not as dominant a supplier of US imports. For example, for the rightmost column—the one that shows products where at least 80 percent of import value originates from a single nation—China is the top one supplier in only around a third of the cases.

In other words, if one looks at the direct source of imports, China is important but not dominant.[14] However, if one uses IO analysis to determine where the directly imported products were actually made, China's dominant role becomes clear. Of course, the results in figure 4 and figure 12 are not directly comparable, but the contrast is striking. The stark differences are indications of just how much exposure is hidden by failing to look through the veil of inputs into the inputs.[15]

Given the finer level of disaggregation that is possible with trade data, we use the same type of analysis to take a closer look at the United States' imports of automotive parts and components, presumably for the Vehicles sector, where supply chain disruptions are a major issue in the public debate and the distinction between final and intermediate imports is fairly clear. The automotive industry is an interesting case since our IO analysis found it to be one of the most exposed to foreign sourcing, and the nature of automobiles allows us to easily distinguish final from intermediate goods in the HTS ten-digit descriptions. Panel B of figure 12 shows a chart that is similar to the one in panel A, but it focuses solely on the 335 imported products classified as intermediate inputs to the automotive sector by the Office of Transportation and Machinery.[16]

14. Evenett (2020) and Goldberg and Reed (2023) note that face value import dependency from China is small in most product categories.

15. Reconstructing panel A of figure 12 for the top two suppliers (instead of just the top one supplier) reveals that more than half of all the products that the United States imports have over 80 percent of their value coming from just two suppliers.

16. We rely on the US Department of Commerce International Trade Administration classification of automotive parts, as proposed by the Office of Transportation and Machinery, "Harmonized Tariff System Codes, Schedule B Codes, and North American Industry Classification Schedule Codes for Automotive Parts," https://www.trade.gov/automotive-parts-tariff-codes.

A comparison of the two panels of figure 12 suggests that the geographic concentration of supply chain exposure for automotive parts is significantly less marked than it is for the average good (which includes many final goods). The top quintile, for example, covers less than 15 percent of products. This coverage is significantly lower than the 25 percent observed for the entire range of imported goods shown in panel A of figure 9. When considering the top two suppliers, this rises to just over 30 percent. This finding is in line with the findings from figure 5 where we saw that the top six suppliers each provided at least 1 percent of manufactured intermediates to the US Vehicles sector.

III. The Shocks: A Typology of Recent and Likely Future Shocks

To organize thinking and discussions about supply chain shocks, we employ a framework that we proposed in previous work (Baldwin and Freeman 2020b; Baldwin, Freeman, and Theodorakopoulos 2022).[17]

III.A. A Typology of Shocks: Types and Sources

Our typology classifies supply chain shocks into two types—idiosyncratic and systemic—and three sources—supply, demand, and connectivity. The combinations are illustrated with examples in table 1. Supply shocks include classic disruptions such as natural disasters, labor union strikes, the bankruptcy of suppliers, industrial accidents, and the like (Miroudot 2020a). They can also include shocks emanating from broader sources such as trade and industrial policy changes and political instability. Demand shocks can come from many sources. At the firm level, they can be instigated by damage to the reputation of a product or company, customer bankruptcy, entry of new competitors, or policies restricting market access. At the aggregate level, they can be triggered by macroeconomic crises, recessions, or exchange rate changes. Connectivity shocks include, most obviously, transportation of goods, but can also include disruptions of communications and restrictions on travel by key personnel.

The threefold categorization of shock sources is not foolproof. Moreover, one shock can lead to another. The shortage of new US cars and trucks, for example, was a supply shock, but it also created a demand surge that

17. A similar breakdown is also put forth in Goldberg and Reed (2023) in terms of what should be considered when judging responses to economic shocks.

Table 1. Taxonomy of Sources and Nature of Shocks, with Examples

	Supply	*Demand*	*Connectivity*
Idiosyncratic (isolated, simple)	Factory closure, labor strikes, extreme weather, etc.	Single product demand surge, etc.	Single port closure, single firm cyberattack, etc.
Systemic (multi-sector, multi-market, complex interactions)	Pandemics, trade wars, large-scale extreme weather, etc.	Sector-wide preference shifts, multi-product, multi-sector boycotts, embargoes, etc.	Massive hurricanes, military conflicts, large-scale hacking, etc.

Source: Authors' elaboration.

disrupted the used car market (Helper and Soltas 2021). Further, connectivity shocks (such as port congestion and container shortages) can emanate from demand shocks that cause stressed logistics systems or physical disruptions like the Evergreen ship getting stuck in the Suez Canal or reduced traffic in the Panama Canal caused by a severe drought (Doermann 2023). In a similar vein, Guerrieri and others (2022) highlight how COVID-19 started as a supply shock and subsequently led to a demand shock. It is also worth noting that not all shocks fall neatly into the three bins. The destabilizing influences of shifts in trade, taxation, industrial norms, or regulatory guidelines, for example, often defy clear categorization as they can concurrently have an impact on supply, demand, and connectivity.

Importantly, the ability to distinguish among the sources of shocks is crucial, as the appropriate remedies typically depend on identifying the source of the disturbance (Baldwin and Freeman 2022). For example, geodiversifying suppliers will not mitigate unanticipated demand shocks.

SYSTEMIC VERSUS IDIOSYNCRATIC SHOCKS While supply chain disruptions have a long history, we believe that there has been a transformation in the nature of these shocks from mostly idiosyncratic shocks to frequent systemic shocks. And we are not alone. The notion that the nature of shocks shifted is shared by business groups that follow supply chain issues closely (ICC 2023; Hong and Betti 2023).

Leaving aside truly unique events such as the 2008–2009 global financial crisis and the 1970s oil shock, most of the supply chain disruptions before 2016 seemed relatively small, independent, and controllable at the firm level. Notable examples include the floods in Thailand that disrupted auto production, earthquakes in Japan that disrupted the electronics industry, as well as labor strikes. As such, supply chain disruptions seemed to be a topic that could be safely left in the hands of private firms and logistics companies, supply chain management strategists, and operations research specialists. These shocks were idiosyncratic in nature.

Since 2016, some global supply chains have experienced shocks that affected many sectors and many countries, and some were long-lasting. Notable examples include wars, pandemics, the economic implications of events like Brexit and the US-China geo-economic tensions, and massive cyberattacks like the Colonial Pipeline shutdown discussed below.

This shift in the nature of shocks is a crucial point. Idiosyncratic shocks tend to be controllable at the firm level and thus not an obvious candidate for policy intervention. Systemic shocks, in contrast, are disturbances that resonate across numerous markets, sectors, and products, having a broad geographical and sectoral reach. As such, they are increasingly uncontrollable at the level of individual firms and thus potentially a target for welfare-enhancing policy interventions.

III.B. State of Disruptions

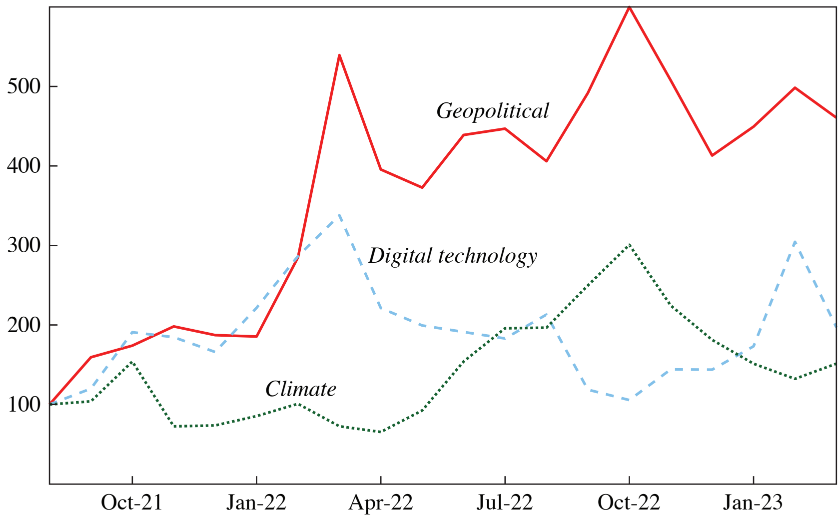
The shocks that emanated from COVID-19 are slowly resolving themselves—at least at the economy-wide level. The Federal Reserve Bank of New York, for example, has developed an index to track the impact of supply chain disruptions (with an eye to their impact on US inflation). This indicator, the Global Supply Chain Pressure Index (GSCPI), spiked at a level that was more than three standard deviations above the historical average in April 2020. The shock faded by October 2020 but then shot up in November 2021 to more than four standard deviations above average. Since then, the GSCPI has fallen.[18] According to the most recent data from July 2023, the GSCPI is nearly a full standard deviation below the index's historical average.[19]

Given that the COVID-19 shocks are fading, it is tempting to think that massive disruptions are a thing of the past and that all the attention being paid to supply chain disruptions by governments and firms is akin to generals preparing for the last war. This is a temptation to resist. While there are no economy-wide data on supply chain disruptions, the COVID-19 shock generated survey-based efforts to gather better and more timely data on shocks. The data, as we shall see, suggest that the supply chain disruption is most definitively not fading, although it is not as intense in 2023 as it was in 2021 and 2022.

18. Federal Reserve Bank of New York, "Global Supply Chain Pressure Index," https://www.newyorkfed.org/research/policy/gscpi.

19. The Bank for International Settlements (BIS), which tracks more classical indicators, comes to roughly the same judgment.

Figure 13. World Economic Forum's Global Value Chain Barometer, 2021–2023



Source: Betti and others (2021), data provided to authors upon request.
Note: Values indexed to 100 in August 2021.

One survey-based gauge, published quarterly by the World Economic Forum (WEF) in partnership with the consulting firm Kearney and utilizing data insights from Everstream Analytics, is the Global Value Chain Barometer (Hong and Betti 2023). In terms of sources of shocks, it focuses on three areas: climate change (especially trade disruptions linked to extreme weather); geo-economic tensions (especially the Russo-Ukrainian War, realignment of emerging-economy coalitions, and trade policy tools that purposefully disrupt trade and investment flows); and digital technologies (especially cybersecurity-related disruption of supply capacities and transportation). After three years of supply chain disruptions driven by the megatrends of climate change, geopolitical tensions, and technological step change, disruption levels seem to have stabilized by 2023:Q1 compared with 2022:Q1, albeit at an elevated level (figure 13). This reflects a combination of a stable trend for new disruptions and firms' improved ability to operate in a more volatile environment. Overall, this suggests that the three big sources of future shocks are not fading in importance.

Another piece of survey evidence regarding current and future supply chain shocks comes from new research by the consulting firm Deloitte, conducted in collaboration with the Federation of German Industries and the

International Service Logistics Association. Their survey, titled "Supply Chain Pulse Check" (Sandau and others 2023), reveals that over half of the supply chain managers from more than 120 German manufacturing enterprises surveyed report a strong to very strong impact on their performance due to supply chain disruptions. A significant majority—60 percent—believe that these disruptions present an even larger problem for the manufacturing sector as a whole. Illustrating the gravity of these supply chain issues—and their potential to worsen—nearly half of the respondents expressed current concerns about a slight to significant increase in the risk of full or partial supply chain failure. These concerned respondents outnumbered those who held the opposite view. Notably, small to medium-sized enterprises indicated a higher level of concern about supply chain disruption and failure compared to large companies.

LIKELY FUTURE SHOCKS Regarding expectations for future shocks, the findings in the Deloitte survey were not optimistic. Almost 60 percent of respondents anticipate no change in the current trend of supply chain disruption, at least in the near-term. Half of them expect a slight improvement in the medium to long term, but over one-fifth foresee the problems becoming slightly or significantly worse in the future.

A similar exercise was undertaken by the Business Continuity Institute (BCI) involving more than 200 supply chain risk management professionals in fifty-eight nations and across seventeen sectors (Elliott, Garcia, and Riglietti 2023). The study found that the reported supply chain disruptions are still more than twice as high as pre-pandemic levels. Almost half of respondents experienced these issues with their closest suppliers at tier 1, while approximately a quarter saw more disruptions with their tier 2 suppliers. Both of these figures exceeded those in the last report (Elliott 2021).[20] Interestingly, the respondents expected cyberattacks and data breaches to be the top threat to supply chains over the coming years.

Looking ahead, the three most cited sources of future systemic shocks are geo-economic tensions, climate change, and digital technology (Hong and Betti 2023; Alicke and others 2022). Geo-economic tensions, for example, have led some actors to use and reshape economic linkages and tools to serve a broader set of strategic goals beyond those that are purely economic, in what some have termed "weaponized interdependence" (Farrell and Newman 2019; Drezner, Farrell, and Newman 2021). For instance, the tariffs implemented by the United States in 2018 were followed by other

20. The 2023 report notes that these high results are partly due to more analysis being undertaken on the performance analytics of supply chains.

countries introducing reciprocal measures to raise trade and investment barriers, often citing geo-economic and national objectives (York 2023; Bown and Kolb 2023). More recently, the Russo-Ukrainian War has not only elevated concerns about supply chains and national security but also triggered a cascade of systemic shocks. These manifest as trade sanctions, boycotts, embargoes, and cross-border restrictions that reverberate through global supply chains, affecting international flows of goods, services, capital, people, and know-how (Goldberg and Reed 2023).

The second source, climate change, is perhaps the ultimate example of radical uncertainty, that is, events whose determinants are insufficiently understood for probabilities to be estimated (King and Kay 2020). Two aspects, however, have clear implications for systemic supply chain disruptions. Extreme weather events have repeatedly knocked production and transportation facilities offline in ways that affect many sectors and many economies (Seneviratne and others 2021). Hurricane Katrina, for example, immediately knocked the Port of New Orleans offline for two weeks and greatly reduced flows through the port for months after. Likewise, heat waves and droughts have forced some electric power plants to reduce output in the United States and France (Barber 2022). On another note, a very different source of shocks concerns future pandemics. Many public health experts expect climate change to induce the migration of species, resulting in novel genetic recombination among animals and thus more zoonotic viruses affecting humans (Randolph and others 2020).

Digital technology is the third source of future systemic shocks. The rapid advance and spread of digital technology in all its manifestations is dialing up the regularity and severity of future shocks in two ways: it is encouraging more activities to shift to the online world where they are vulnerable to accidental and malicious disruptions, and it is boosting the abilities of and incentives for hackers to interrupt normal business activity (Burt 2023). A well-known example is the Colonial Pipeline attack (Easterly and Fanning 2023). In 2021, a criminal hacking group called DarkSide carried out a cyberattack that caused a weeklong disruption in the supply of gasoline to the eastern parts of the United States. The company that owns the pipeline, Colonial Pipeline, had to shut it down to stop the cyber infection and prevent further damage. Since this pipeline was responsible for delivering almost half of the fuel used on the East Coast, the attack led to widespread panic among consumers and a significant increase in fuel prices. Cybersecurity is continuously improving, but so are the skills of criminal and state-sponsored hackers. In this way, digital technology still poses significant risks to supply chain operations around the world.

The last distinction, which is general and applies to all combinations of shocks listed in table 1, is the difference between known unknowns and unknown unknowns. There exists a spectrum of shocks based on our level of awareness and anticipation. At one end are the known unknowns—events or situations we recognize might occur but whose timing and exact form are uncertain. For instance, labor strikes at Paris Charles de Gaulle Airport can be somewhat predicted, given that such events have historical precedents and observable trends. Preparing for these kinds of shocks is relatively straightforward, as we are aware of their potential occurrence. At the opposite end of the spectrum are the unknown unknowns—events without forewarning or precedent and therefore unpredictable in both timing and nature. A fitting example would be the specific characteristics of a future pandemic. While we may anticipate another pandemic based on past occurrences, predicting its exact nature, method of spread, health and economic impacts, and other details is inherently difficult or even impossible.

To provide examples for our policy discussion in the next section, we close this section with a quick recap of recent events before making the case that the nature of supply chain shocks has shifted from idiosyncratic to systemic.

III.C. Brief History of Recent Supply Chain Disruptions

The years 2020–2023 were a wild roller-coaster ride for the world's production networks—a journey into uncharted waters of supply chain bottlenecks, unanticipated dependencies, feedback loops, and formerly hidden interlinkages. But despite the media attention they received, such large-scale supply shocks were not a new thing in 2020. Indeed, who could have imagined, back in early 2019, that the grand challenge to global supply chains would arise from a tiny, malevolent ribbon of RNA?

From 2016, the disruption narrative revolved around geo-economic tensions. These included tariffs imposed by the United States on many of its trade partners and those nations' imposition of retaliatory tariffs (Bown 2017, 2021). The unpredictability of economic policymaking also became a source of disruption. There was also discussion among academics, policymakers, and international organizations about the disruptive possibilities of climate change. These concerns persist today, but their significance was overshadowed by the reach, severity, and lasting impact of the COVID-19 pandemic.

The pandemic took root in late 2019 and surged repeatedly until May 2023 when the World Health Organization officially declared its end as a global health emergency (WHO 2023). A by-product of the disease was that countries very directly and very expressly disrupted production by imposing stay-at-home measures or reduced-mobility policies that halted factory operations in many sectors worldwide. Other policies also directly disrupted shipping. For example, in an attempt to stall the spread of the virus, many major ports prohibited crew changes without a fourteen-day quarantine, which had a severe impact on transportation and supply chains (Heiland and Ulltveit-Moe 2020; Bai and others 2022).

As nations and businesses were adapting to the virus and related health measures, another source of disruption emerged in 2021. Prevented from spending as much as usual on services like food and entertainment, consumers redirected their expenditures toward physical goods, sparking a resurgence in global demand for manufactured goods. Many such goods were made in Asia or with parts from Asia. This shift in spending patterns intensified disruptions stemming from production and transportation disturbances. The scale and duration of this shift exceeded expectations, and supply struggled to meet surging demand. Critical inputs, such as semiconductors, faced shortages. This had an impact on a range of downstream industries, especially the truck and automobile sectors. The collective effect of these disruptions reveals how fragile and unprepared GSCs were to respond to sudden changes in demand patterns.

An important consequence of this combination of supply and demand shocks was the misplacement of shipping containers due to consumers shifting from in-store to online shopping (Tirschwell 2022). Many of these containers, filled with Asian-manufactured goods, ended up at online fulfillment centers lacking sufficient storage capacity. Furthermore, as the demand surge primarily involved Western demand for goods produced in Asia, trade flows became imbalanced. As containers accumulated in North Atlantic economies, a container shortage emerged in Asia, leading to increased shipping costs and delays. These bottlenecks affected final goods as well as crucial parts and components, ultimately having an impact on manufacturing in the United States and Europe. The pandemic waned and economies reopened in mid-2022, yet global manufacturing remained off-balance. Disruptions persisted due to a near-perfect storm of imbalances. By this, we refer to a convergence of factors—both predictable and unpredictable—that threw supply, demand, and transportation out of equilibrium. The disruptions were so large and so broad that they contributed to an inflationary surge in advanced economies (De Guindos 2023).

The parade of once-in-a-lifetime shocks continued. The Russo-Ukrainian conflict led to sanctions, embargoes, and boycotts, driving commodity and energy prices to soar. This fueled double-digit inflation, which had been absent for decades, introducing macroeconomic disruptions to production-level shocks. Central banks raised interest rates and global growth slowed. But the surprises did not end there.

A third wave of supply disturbances arose when a new variant of the virus spread to China, triggering severe lockdowns in key centers like Shanghai in the spring of 2022. This hampered shipping and the production of intermediate parts, serving as a less intense but no less significant reminder of the evolving nature of supply chain shocks. Then came China's significant policy reversal—shifting from a stance of zero COVID-19 to almost no policy on COVID-19. After the wave of infections receded, this unleashed pent-up demand from Chinese consumers. China's policy reversal is significant because it not only influences global supply chains but also reveals how quickly governmental policies can change, adding another layer of unpredictability to supply chain planning.

IV. Policy: Robustness and Resiliency

In this section, we explore how the broader, more macroeconomic perspective of the economic approach to supply chains can offer insights that could be valuable in formulating policies to reduce, avoid, or mitigate supply chain disruptions. We start with a critical distinction that is pervasive in the logistics and supply chain management literature (Brandon-Jones and others 2014) but largely absent from the recent economic literature—Miroudot (2020a) is a notable exception—namely, underscoring the difference between robustness and resiliency when it comes to supply chain risk management.

IV.A. Adjusting to Risk: Robustness versus Resilience

Businesses and governments have always been aware of the potential risks of disruption. As the surveys discussed in the previous section showed, firms have put into place adaptive strategies that draw from two vital concepts: robustness and resiliency (Brandon-Jones and others 2014). These words have very similar meanings in English and in fact are sometimes used interchangeably or in tandem in the public discourse surrounding supply chains. To clarify, we start with an example that helps spotlight the differences. The example concerns strategies to address the challenges created by electric power outages.

Most households and businesses understand that the power will occasionally go out and embrace pro-resilience strategies so that they are minimally affected when outages occur. Otherwise stated, they know the shock will hit and they know operations will be disrupted, but they arrange things to reduce the disruptions and bounce back quickly after the disruption subsides. In contrast, most large hospitals adopt very different strategies, namely, pro-robustness strategies (FEMA 2019). They have multiple alternative electricity sources, including batteries and generators, to ensure that they can continue operating despite the power outage. In a nutshell, the goal of robustness is to have backups that allow the show to go on while the disruption is occurring. The goal of resiliency is to get the show back on the road as soon as possible.

At one level of abstraction, both seek to reduce the duration of production disruptions, but the supply chain risk management literature separates them since the firm-level strategies aimed at robustness are quite different from those aimed at resiliency (Simchi-Levi, Schmidt, and Wei 2014; Simchi-Levi 2015). A supply chain is robust when it continues to operate despite shocks. This is often achieved by engineering supply chains to include fail-safes, redundancies, and geo-diversified supply sources, along with maintaining appropriate inventories of critical inputs. On the sourcing front, robustness signifies cultivating a diversified array of suppliers poised to deliver identical inputs, thereby immunizing the business process against disruptions originating from a single supplier. Within the company's own production sphere, robustness entails maintaining multiple manufacturing sites for in-house inputs and finishing of final goods. In all scenarios, amassing substantial inventory levels and buffer stocks throughout the supply chain, as well as relying on standardized inputs from multiple suppliers, enhances robustness (Sáenz and Revilla 2014).

Resilience relates to the system's capacity for rapid recovery postcrisis, and as such it is a more dynamic concept. The goal is for the supply chain to bounce back from disruptions in a manner that is both efficient and expedient. The essence of resilience lies in flexibility and adaptability, which could take the form of swiftly switching suppliers, adjusting production schedules on the fly, or tweaking products as required (Sá and others 2019; Miroudot 2020b).

Robustness and resilience are not binary options. They are two sides of the same coin in the risk management world. For instance, relying on standardized inputs in a production process (a robustness strategy) could also be a resilience strategy insofar as it would allow flexibility and adaptability in the face of a shock. To summarize, a robust supply chain offers a buffer that can soak up a certain degree of disruption without significant operational impact, buying the system time to respond. In tandem with this, resilience enables the system to adapt, recover, and thus minimize long-term negative impacts.

TRADE-OFFS IN BUILDING ROBUSTNESS AND RESILIENCE Building robustness and resiliency into supply chains involves distinct sets of strategies. When the shocks come from the supply side, this requires some form of redundancy. This could manifest in a broad and geo-diversified portfolio of suppliers for inputs, multiple production sites, or large inventories. Setting up and maintaining these redundancies necessitates higher immediate operational costs. Indeed, it can be expensive to manage relationships with many suppliers, especially when the input requires extensive checking and certification for quality and fits with the rest of the production process. Further, the spreading out of orders among multiple suppliers may dilute buying power and elevate costs associated with contract supervision and enforcement.

As mentioned, one of the most direct means of establishing robustness is to hold substantial inventories of parts and components, but this can be expensive and even impractical (for example, if warehouse space is not available). One example was the well-anticipated, post-Brexit uncertainty that British carmakers faced when the end of their frictionless trade with the European Union was looming, but they did not really know how well the new system would work. Holding inventory was an obvious idea, but the problem lay in the scale of the challenge. Today's cars are made up of tens of thousands of parts, ranging from nuts and bolts to engines, transmissions, and electronics. Beyond the financial costs of maintaining extensive inventories, the logistical challenge of storing such a wide range of components is formidable.

Moreover, when it comes to highly specialized parts and components, the costs of ensuring that these products meet quality standards and integrate smoothly into the existing production process can make it prohibitively expensive to engage with many suppliers. In such cases, the buyer may have to strive for resiliency rather than robustness. This is why single-sourcing and long-term partnerships often emerge as risk management tactics. While such a strategy might compromise robustness if the supplier encounters risks, the benefits include avoiding the sunk costs of switching suppliers and securing investments from the existing supplier in facilities and practices that can abbreviate disruptions. Even though a serious shock to a single supplier may disrupt overall production, the buyer may choose to put plans in place for quick recovery.

Constructing resilience could involve fostering the ability to adjust production schedules and modify products as required (Miroudot 2020b).

As resilience is likely to involve actions that were not anticipated, off-contract trust among suppliers and buyers (or direct control via ownership) is important in boosting resilience (Sá and others 2019; Dubey and others 2019; Bode and others 2011). In the extreme, resilience may require buyers to functionally control the suppliers or at least maintain long-term relationships that foster sufficient trust. As usual as it is in economics, the choice is not between risk diversification and reliance on lower-cost, higher-quality inputs; it's about finding the right balance. The extra costs today of diversification must be weighed against the expected future benefits of having a supply chain that can carry on in the face of shocks. The possibility that public authorities may have a different evaluation of the trade-off is a key justification for supply chain policy.

IV.B. Do We Need Policy? The Wedge between Private and Public Risk Evaluation

Baldwin and Freeman (2022) introduce an analogy with portfolio theory to discuss the public-private evaluation of supply chain risk. They base this analogy on the standard portfolio model, highlighting the potential existence of a wedge between public and private risk evaluations. While firms are concerned about risks, they also value cost savings. A societal appraisal of this trade-off might prioritize risk reduction more or less highly than the individual firms making the decisions.

EXAMPLES OF PUBLIC-PRIVATE WEDGES IN RISK PERCEPTION What are some examples of these public-private wedges? It is useful to turn to two industries where most governments actively intervene to make the supply chain more resilient: the food sector and the military equipment sector. In the food sector, farmers use various tactics to protect crops from shocks like pests, diseases, and uncertain rainfall. But while the cost to an individual farmer of a bad harvest is limited, a general failure may lead to famine and social upheaval. The wedge here exists because market prices do not fully reflect the social cost of famine or hunger. The classic pro-resiliency government policies in this case are to subsidize production, control prices, and maintain sufficient inventories.

In the realm of military equipment, many governments systematically favor domestic production. While there may be protectionist motives behind such policies, one rationale focuses on the ability to maintain armament production even during wartime. The societal risks associated with a lack of military equipment are even harder to quantify than those in food production. An inability to produce arms and military supplies could lead to loss of territory, loss of life, or loss of sovereignty. In a general way, it is natural to assume that private firms, which are primarily profit-driven, will underappreciate these social costs of supply disruptions. Protection of basic metals sectors, and steel in particular, is often justified on national security grounds.

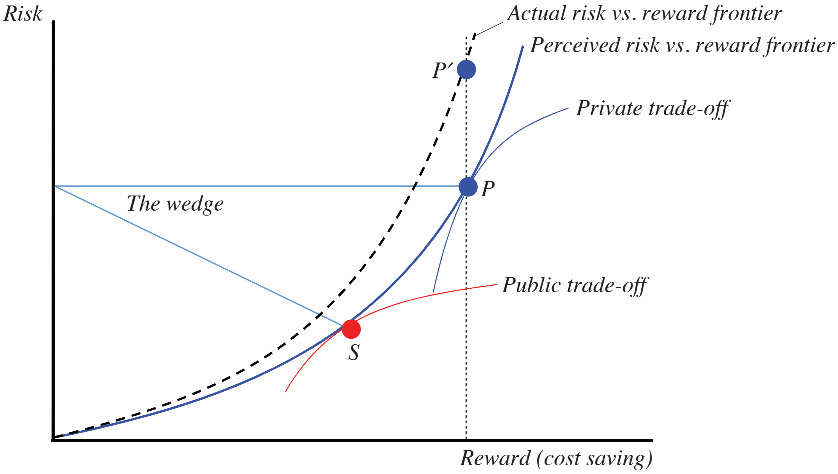
In both the farms and arms cases, we could say that governments knew that the private sector cared about risk, but their caring was mostly limited to their bottom line while the societal cost of major disruptions could be much higher, encompassing factors like social upheaval and loss of life. Another way to rationalize the near-universal intervention of governments in the farms and arms supply chains is the prospect theory of Tversky and Kahneman (1973). This theory explains how humans tend to act in seemingly irrational ways in the face of uncertainty. It stresses the role of present-biased reference points, pervasive loss aversion, and the importance of framing effects.

In the financial sector as well, governments seldom entrust risk management entirely to private entities. The justifications for the interventions are wide-ranging, but many are rooted in information asymmetry, inadequate information, or some agents' inability to process information correctly. These range from investor protection and transparency rules to market stability policies.

Elements of the justifications from these three examples are clear in the recent spate of risk management policies put forth by the Biden administration (White House 2021). The executive order asserts that structural weaknesses in United States supply chains have long existed, but it took the COVID-19 pandemic to bring them into the mainstream. The document notes the need to "strengthen critical supply chains and rebuild [the US] industrial base" (White House 2021, 12). The Biden administration's policy has focused on four sectors that share some of the characteristics of the food and military supply sectors on the one hand, and the financial sector on the other. These are: semiconductors and advanced packaging; large-capacity batteries; critical minerals and materials; and pharmaceuticals and related active pharmaceutical ingredients.

Semiconductors and batteries have become critical to the production of many manufactured goods, including a wide range of armaments. The justification for public policies may thus be linked to those that apply to the arms industry. The advanced packaging concern came to light when the US rollout of COVID-19 vaccines was delayed by a lack of glass vials with the necessary quality. The inclusion of pharmaceuticals can be thought of as akin to the justifications for intervention in the food sector. While individual producers are aware of risks and take active measures to reduce

Figure 14. The Risk-Reward Wedge and Public Policy



Source: Baldwin and Freeman (2022), adapted with permission from the *Annual Review of Economics* 14, copyright 2022 by Annual Reviews.

them, they do not fully incorporate the social costs of severe supply shortages into their business models.

THE WEDGE DIAGRAM Every economics student learns that policy interventions can potentially rectify market outcomes when there is a wedge between the private and public evaluation of the consequences. This happens when there is a gap between private and societal risk assessments, or when collective action challenges cause information gaps, leading firms to operate without full information. Figure 14, presented in Baldwin and Freeman (2022), illustrates these points.

The central idea that the diagram illustrates concerns a trade-off between cost savings and risk. That is, firms can lower costs by centralizing production in cost-efficient areas. However, this cost-saving approach increases the risk associated with centralizing all production. The diagram illustrates this trade-off with the upward-sloped risk-reward curve that is bowed outward. This curve simply asserts that additional cost savings come with heightened risks. The risk-reward frontier curves upward, indicating that the risks-versus-cost-savings trade-off steepens as costs fall.

The downward-curving private-evaluation curve is an indifference curve. It reflects the trade-off firms face on the economic side. That is to say, while firms dislike risk, they like cost savings. The “Private trade-off” curve depicts this relative evaluation. This indifference curve is bowed downward since we assume that firms worry more about risk as the risk level rises. In other words, firms need ever greater increments in cost savings to justify ever higher risk.

The diagram also plots the public evaluation of the risk-reward tradeoff, which is drawn assuming that the government is more risk-averse than private firms. Various reasons—such as those discussed above in the farms and arms sectors—can justify this discrepancy. For instance, companies might overlook the broader macroeconomic ramifications of supply disruptions, focusing solely on their own performance. Disruptions at one supply chain point could result in losses downstream, but upstream entities might not factor in these potential losses.

As mentioned, such a gap between public and private risk perceptions is easy to envision in critical sectors like medical supplies or food production or for other strategic inputs like semiconductors. As illustrated in figure 14, private entities, in the pursuit of their private goals, might be willing to embrace more risk (as shown by point *P*) than would be socially optimal (point *S*). This difference between societal and private preferences creates a discernible gap and hence a market inefficiency. This inefficiency, in turn, suggests a rationale for policy interventions that reduce supply chain risk.

Importantly, this wedge is not a classic Pigouvian wedge that arises from divergences between public and private evaluations of the marginal benefits or marginal costs of an activity. Our wedge is based on risk perceptions. As drawn, the government is more worried about risk than the private sector, but it could plausibly go the other way. For example, the government would want the firm to take more risk with its supply chain in order to accelerate the delivery of, say, vaccines to the market.

The diagram also sheds light on another possible reason for policy action: information problems. As discussed in section II, firms often have incomplete information about their supply chains due to their sheer complexity. The McKinsey Global Institute's estimate that General Motors had over 18,000 suppliers serves as a telling example; monitoring all these suppliers would be nearly impossible (Lund and others 2020). Moreover, the same study found that nearly half of the companies that were assessed either had no detailed information on their supply chains or had information only on their immediate, tier 1 suppliers. With such a complex web of suppliers, it's hardly surprising that firms may inadvertently expose themselves to more risks than they assume. In other words, the actual risk landscape might be far more perilous than perceived, leading firms to make choices that unknowingly expose them to undue risks.

V. Concluding Remarks

Our paper looks at the three fundamental elements of supply chain disruptions: the links that create the possibility of disruption; the shocks that create the disruptions; and measures aimed at taming or avoiding the disruptions. Here in the concluding remarks, we put forward some conjectures on the implications of our discussion of the three elements.

Starting with the links element, a core message of our paper is that the United States' exposure to foreign supply chains is much bigger than it appears at face value, but it is not that big at the macro level. There are two distinct points in this bigger-but-not-big finding.

First, by any measure, the United States buys at least 80 percent of all industrial inputs from domestic sources. Thus, at an aggregate level, its foreign exposure is hardly alarming. However, while this may be reassuring, it is important to note that supply chain disruptions rarely occur at the macro level. The 80 percent figure was not relevant when the US auto sector shuttered factories due to a lack of semiconductors, or when buying home office electronics became problematic due to a demand surge and logistic snarls. This observation serves to provide some perspective on the recent public debate on foreign supply chains. Concerns about foreign exposure should be directed to particular products, not US manufacturing as a whole (more on this below). This is our conjecture as to what the "not big" part of our results means. The bigger part of bigger-but-not-big suggests a very different conjecture.

US supply chain exposure to some foreign suppliers is much higher than it appears to be using standard trade statistics. We calculate that this is especially true for China. By any measure, China is the United States' largest supplier of industrial inputs. But taking account of the Chinese inputs into all the inputs that American manufacturers buy from other foreign suppliers—what we call look-through exposure—we see that the US exposure to China is almost four times larger than it appears to be at face value.[21] A second aspect of hidden exposure arises from the fact that China's dominance of the United States' imports of industrial inputs came rather suddenly. This might help explain why the basic point was not brought to the fore until recently.

21. The same hidden exposure point holds for Taiwan and South Korea. Their look-through exposure is 3.5 times larger. For Japan the figure is 3.1. Nonetheless, these countries have a much smaller absolute face value and look-through exposure overall.

Combining the two points from our links results, in conjunction with the fact that all major economies are also highly reliant on Chinese inputs to their inputs suggests that an across-the-board decoupling of the US and Chinese manufacturing sectors is unlikely to be cheap, quick, or even feasible.[22] More research is needed to quantify this point, but recent studies all point to the fact that a US-China decoupling is likely to be very damaging economically to the United States and the world as a whole (Góes and Bekkers 2021; Freund and others 2023; Métivier and others 2023; Aiyar and others 2023).

Moreover, taking the face value versus look-through distinction to heart suggests that the latter measure is more relevant in assessing whether policies aimed at reducing US exposure to Chinese manufacturing will have their desired effect. For instance, simply substituting away from imports from China to, say, Vietnam may do little to reduce the look-through dependence on Chinese production if the Vietnamese exports to the United States depend on Chinese inputs. This important point is made empirically by Alfaro and Chor (2023).

Turning to the second element of supply chain disruptions, the shocks, our discussion suggests that the United States is facing a new reality when it comes to supply chain shocks. We argue that the nature of shocks has shifted. While idiosyncratic shocks continue to produce challenges for manufacturers around the world, many of the recent and likely future shocks will be systemic. Here idiosyncratic shocks are those that are isolated and limited in scope, while systemic shocks have impacts that affect multiple sectors and regions and may be long-lasting. In addition to these two types of shocks, we underscore that the source of supply chain shocks can be either demand-driven, supply-driven, or affect connectivity—and that these three categories are often interconnected.

While there is no way to predict future shocks—and in particular those that are systemic in nature—evidence gathered from surveys of supply chain risk managers coupled with the costly, long-lasting adjustments that firms are making to their supply chain organization, provides evidence that the nature of shocks has shifted. These surveys highlighted three central sources of future shocks: climate change, geo-economic tensions, and accidental and malicious digital disruptions.

22. As mentioned in section II.C., our look-through measure also tells us that it is not just the United States that is heavily dependent on China for industrial supplies; every major manufacturing nation in the world sources at least 2 percent of its industrial intermediates from China (Baldwin, Freeman, and Theodorakopoulos 2022).

Laying our findings on shocks end to end with our findings on links leads to a very clear policy message. Concerns about supply chain disruptions should not be overblown, but they should be taken seriously since they are likely to be with us for many years to come.

The final element of our paper concerns policies that are aimed at reducing the impact of supply chain disruptions. As an essential background to policy considerations, we highlighted here the need to think hard about rationales for public policy interventions. A second bit of essential background that we touched upon is the nontrivial distinction between robustness and resiliency in supply chains, which is taken as critical in supply chain risk management research. The need for a policy intervention rationale is clear, but we focus on divergence in the evaluation of risk by the government and private sector, not the traditional situation that focuses on market inefficiencies.

Because firms actively choose the risk level of their supply chains (to the extent that they have visibility of their suppliers and suppliers' suppliers), any public policy intervention should be based on the presence of a public-private wedge in the trade-off between cost savings and disruption risk. Given the vast diversity in supply chains, we argued this point by analogy, drawing attention to sectors where most nations have chosen to interfere with the private sector's optimal combination of low-cost sourcing and concentration of supply chain risk. In the farms and arms sectors, for example, governments have long implemented expensive policy interventions to encourage domestic production and diversified sources. In these sectors, the public-private wedge arises from many underlying factors, but often they involve the fact that serious disruptions can create large-scale societal problems. As the private sector has little incentive to fully internalize such problems, it is easy to imagine that the wedge is large in these sectors.

Do the sectors that have recently been the focus of government supply chain policy fit this bill? In the United States, Europe, and Asia, semiconductors seem to have slipped into the same category as farms and arms in the sense that governments around the world have decided that they cannot rely solely on the private sector to control supply chain risks. In the United States, the Biden administration has also put some pharmaceutical products as well as large-capacity batteries into the farms and arms category. Without detailed simulations of the economic and social costs of disruptions in these products, it is impossible to comment precisely on the merit of these governmental choices. But, given the lack of incentives for firms to consider the broader societal costs of extreme events, it is easy to think that there are wedges that would justify intervention in these sectors.

V.A. Directions for Future Research

It is plain that there is much, much more that could be done to shed light on the exposure of US supply chains to future shocks. One direction would be to explore the use of granular data, such as firm-specific, transaction-level data or fine-grained geographic data.[23] In particular, it would be very helpful to have more disaggregated ICIO tables at the country and industry dimensions to gain a deeper understanding of supply chain vulnerabilities and the propagation of disruptions in further detail. It would also be useful to more fully document how supply chain exposure became so concentrated geographically. Adding econometric investigation would also be an important contribution. The OECD, for example, has used some of the look-through measures we developed in our earlier work to demonstrate that they provide a more robust empirical accounting for the transmission of shocks than do face value measures (Schwellnus, Haramboure, and Samek 2023a; Schwellnus and others 2023b). The last point we mention is the extension of the entire face value versus look-through distinction to an evaluation of the exposure of US manufacturing sectors on the sales side, that is to say, the exporting side.

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23. To be sure, additional measures of supply chain exposure are being developed, in particular using product-level data. For instance, concerned primarily with the possibility of supply disruptions, the European Commission (2021) and Arjona, García, and Herghelegiu (2023) recently proposed a methodology for measuring the European Union's strategic dependencies and vulnerabilities at the detailed product level, which relies on the computation and use of three indicators relating to the concentration of EU imports from non-EU sources, the importance of non-EU imports in total demand, and the substitutability of non-EU imports with EU production.

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Comments and Discussion

COMMENT BY

PINELOPI K. GOLDBERG At the Spring 2023 *Brookings Papers on Economic Activity* Conference, I presented a paper, written jointly with Tristan Reed of the World Bank, on a closely related topic, that is, deglobalization trends amid the waning political and popular support for free trade (Goldberg and Reed 2023). So unsurprisingly, this topic is close to my heart. One of the questions that we raised in that paper was "How do we increase resilience?" We suggested that, in order to make progress in answering this question, we need to start by defining what resilience is.

As a starting point, we proposed one definition that Markus Brunnermeier had put forward in his book, *The Resilient Society*: resilience is the ability to "bend but . . . not break" (Brunnermeier 2021, 2). In his book, Brunnermeier compares a reed to an oak to contrast resilience with robustness. The reed sways even with the slightest breeze but does not break when the wind is strong. In contrast, the oak can withstand light winds, but if the wind is strong enough, then it breaks. We pointed out that, for this general notion of resilience to be useful, we need to operationalize it and benchmark it. This is not something that economists can do by themselves as it involves value judgments that need to be made by the society as a whole. Finally, we emphasized that with this foundation in place, we need to figure out how to measure resilience.

Against this background, the contribution of this paper is on the measurement side. Baldwin, Freeman, and Theodorakopoulos describe an important measurement exercise. Its implications for shocks and resilience are discussed toward the end. My overall reaction is that, in order to make progress

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on measurement, we need to have first resolved the conceptual issues laid out above: we need to have a clear idea of what we need to measure and why.

There are many commonalities between the taxonomy presented at the end of this paper and the taxonomy presented in Goldberg and Reed (2023). For reference, I reproduce here the schematic from Goldberg and Reed (2023, 367). As we emphasize in our article, "resilience" cannot be defined without reference to a specific shock. I will not go over our taxonomy in detail given that it is explained in our *BPEA* article, but let me highlight two issues that will be important in my discussion.

Relevant considerations when defining "Resilience."

- Nature and magnitude of shock:
  - Supply, demand, or both
  - Sector-specific, country-specific, or both
  - Idiosyncratic or systemic
- Time horizon (short-, medium-, or long-run):
  - Dependent on sector (e.g., food, medicines, where time is of the essence)
  - Dependent on (possibly non-homothetic) preferences (e.g., consumers in rich countries without well-developed public transportation may consider a car a necessity)
- Level of aggregation
  - Economy
  - Industry
  - Firm
  - Household

The first is the time horizon. When we talk about resilience, are we thinking about resilience within a week, which may in fact be the appropriate time horizon if we are concerned about medical supplies? Or do we have in mind a longer time horizon, which may be more relevant if we are considering the purchase of a new car, for example?

The second issue is the appropriate level of aggregation. Is the concern about one particular plant or firm closing down in response to a shock; about a sector, a region; or about the aggregate economy?

The answers to these questions will be context-specific. At any rate, we need to have a clear idea what we are after before we attempt to measure it.

As said earlier, the contribution of this paper is to measurement. The measurement exercise is expertly done and well described in this paper as well as a companion National Bureau of Economic Research (NBER) working paper that provides many additional details (Baldwin, Freeman, and Theodorakopoulos 2022). I will not comment on the specifics of measurement in the rest of this discussion. Instead, I will focus my comments on the implications of measurement, first for trade policy evaluation, and then for the question of resilience. But first, a brief overview of the exercise carried out in this paper.

OVERVIEW OF THE MEASUREMENT EXERCISE Briefly, what is the measurement exercise? What the paper essentially does is measuring the share of each country in intermediate input imports in the United States. There is an important distinction between the face value measure (the direct bilateral imports of intermediate goods) and the look-through measure (the imports of intermediates you get if you take into account the entire input-output structure).

For the latter, one needs inter-country input-output (ICIO) tables that provide information on the input-output relationships for the entire world. The main drawback of the input-output tables is that they are only available at the very aggregate level. The authors are clear about this limitation: in the paper, they have seventeen manufacturing sectors. The authors' main message is that, based on the look-through measure, China is much more important than one might think based on the face value measure. Not only that, but this measure has also grown. If we compare 1995 to 2018 (figure 7 in the paper), the share of China has increased substantially.

Judging this exercise in the context of the literature, one might wonder why we need yet another global value chain (GVC) measure. There is already extensive literature on measuring GVCs in trade.[1] The answer is that most of the measures (as the authors point out) were focused on measuring backward or inward integration and inferring the net value of trade. They were not focused on measuring the exposure of the domestic economy to shocks, which is the focus of the present paper.

As a side note, an interesting aspect of the earlier literature is that one of its motivations was to show that China was not as important in international trade as people thought (in gross terms, China was dominant, but less so in net value terms). In this paper, the motivation is the exact opposite, namely, to show that the dependence on China has increased substantially. It is a very different point of view.

IMPLICATIONS OF MEASUREMENT RESULTS

Implications of results for trade policy evaluation. We can debate what the paper's results mean for resilience, but a clear message is that a complete de-Chinafication of the US economy, that is, a complete decoupling

1. See, for instance, the World Bank's *World Development Report 2020* on GVCs.

of the US economy from China, may be very costly, if not impossible. Let me explain.

One of the most valuable applications of the measurement exercise is its use in the evaluation of trade policy. The recent US-China trade war provides an apt example. In 2018, the United States imposed tariffs on China, expecting a reduction of Chinese exports to the United States. This expectation was confirmed: the US tariffs and the subsequent retaliation by China reduced bilateral trade between the two countries.[2]

I have contributed to this topic myself (together with various coauthors), but a more recent paper by Alfaro and Chor (2023), presented at the Jackson Hole Symposium in August 2023, provides an up-to-date picture of the US-China trade. Their data include the latest export restrictions that the United States has imposed on China. They document that the bilateral trade between these two countries, including the bilateral imports from China to the United States, has decreased sharply. These results are interpreted as evidence that the United States' decoupling from China is happening at a fast rate.

Now, the results of the present paper cast Alfaro and Chor's (2023) results in new light. Baldwin, Freeman, and Theodorakopoulos suggest that the dependence on China may not have been reduced as much as Alfaro and Chor's face value measure suggests. As an example, consider the role of Vietnam. As Chinese imports in the United States become more expensive due to tariffs, there is a substitution in the United States toward imports from Vietnam. However, the look-through measure provided in the present paper suggests that, in order to produce these Vietnamese products, the Vietnamese need to use Chinese intermediates.

This is a different argument from the one initially made that the Chinese could simply reroute their exports through Vietnam to evade US tariffs. This is not rerouting. Instead, the point is that, to produce products in Vietnam, you need to use Chinese intermediates. In this case, an increase in the US imports from Vietnam may indirectly increase the US imports of intermediates from China.

Whether this is important or not, I do not know. I have to say that in my work with Fajgelbaum, Khandelwal, Kennedy, and Taglioni, we did not find that the Chinese global exports increased as a result of the trade war. But we did uncover some unexpected patterns regarding the response of global trade flows to the US trade war (Fajgelbaum and others 2023). One can only make sense of these patterns if one accounts for all global

2. See Fajgelbaum and others (2020, 2023).

input-output relationships and their reallocation in response to the trade war. Therefore, I believe this is an important area for research, and I am pleased to see someone working on it.

The authors are ideally positioned to address such questions. The new ICIO tables will be coming out at the end of the year. A natural next step is to repeat the exercise presented in this paper with the more recent data that reflect the recent actions of the United States vis-à-vis China and vice versa, and compute the updated look-through measures in each sector. It would be fascinating to investigate—using the look-through measures—whether the increasing US dependency on China documented in the present paper has been slowed down or reversed due to recent US trade policy. If it hasn't, this would provide support to the argument that the US trade policy has been ineffective in achieving decoupling from China, and that a de-Chinafication of the US economy may be infeasible. If it has, the natural question is how, given that the US imports from other countries (Vietnam, in my example above) use Chinese intermediates. There is no point in speculating about answers and mechanisms when we do not have the facts yet. But I am looking forward to learning about the facts based on what I hope will be the authors' next paper.

There is one caveat, however. While there is nothing the authors can do about it, it is worth keeping in mind that the sectoral level of the ICIO tables may be too aggregate to capture some of the interesting action.

The caveats associated with aggregate data in the context of GVCs are explored in De Gortari's (2019) work. De Gortari focuses on the automobile value chain of Mexico. He shows that the percentage of intermediates sourced from a particular country may be specific to the particular brand produced in Mexico and to the destination to which this brand is exported. For instance, Mexican exports of cars to the United States use on average 74 percent of US value-added. In contrast, Mexican automobile exports to Germany use only 18 percent of US value-added. So the input-output relationships are specific to each product/export destination pair.

In the present context, this means that we may not see a decline in the average share of total (direct plus indirect) intermediate input imports from China at the ICIO sectoral level, though it is conceivable that the US actions have reduced this share in more disaggregate product categories, to the extent that they have explicitly targeted such categories. I will come back to these aggregation challenges below.

Implications of results for resilience. Inferring resilience is the main motivation of the paper and an issue of great concern these days. A key figure in the paper is figure 4, which shows that the look-through share of

China in US manufacturing inputs is 3.5 percent on average, and as high as 6.3 percent in "Clothes."

Is this high or low? We do not know. This is one case where the need for a benchmark becomes apparent. This is also why I pointed out at the outset that without a benchmark in mind, it is not possible to evaluate the figures presented in this paper.

A further interpretation difficulty arises from the fact that the input shares are not sufficient statistics for dependency or resilience. They can serve as red flags. It is useful to have information on input shares, but such information is not sufficient by itself.

The issues here are analogous to those that come up these days in the discussion about competition and antitrust. Industrial organization economists have emphasized that market shares and concentration indexes are not sufficient statistics for competition. They are red flags, but one needs much more information and economic analysis to establish market power. In the present context of resilience, it is natural to associate resilience with the availability of alternatives and the ability to readily substitute toward them. But then, what one needs to judge resilience is the substitution elasticities on the demand side and the supply elasticities at a micro level. These elasticities in turn depend on the aggregation level. At a disaggregate level, many relationships and production technologies are Leontief; in contrast, substitutability could be much higher at a higher level of aggregation. Substitutability also depends on the relevant time horizon.

Coming back to my introductory remarks, this is precisely why the level of aggregation and time horizon of the analysis are important. I would argue that most of the policy issues we are concerned about these days that are related to resilience, often play out at a much more granular level than at the sectoral level of this paper's analysis. At that level, technologies are often Leontief, and average shares are not informative about the degree of dependency. Let me give three examples.

The first example comes from the work of the other discussant, Benjamin Golub (Elliott, Golub, and Leduc 2022). The authors motivate their analysis by providing a specific example of a relationship-specific investment in commercial airspace: the Airbus A380 uses a particular engine produced by Rolls-Royce, the Trent 900 engine. If Rolls-Royce has a disruption, Airbus cannot substitute, at least not in the short run, toward another engine. Someone might say, well, this is something that affects Airbus. Is that an issue that should worry all of us? In this particular case, given that the aerospace industry is an international duopoly with Airbus on one hand and Boeing on the other, it is an issue that is important, not just for Airbus and for Europe, but also for the United States and the world as a whole. In this example, the bottleneck arising from a potential disruption plays out at a very granular level, which would not be captured in sectoral data.

The second example is from the semiconductor industry. Why is there so much concern about Taiwan? Looking at figure 4 in the paper, the US input import shares from Taiwan are below 1 percent in every sector, even when one employs the look-through measure. Based on these numbers, one would not have thought the US dependency on Taiwan to be significant. However, it turns out that about 92 percent of advanced logic capacity (i.e., semiconductor chips that are less than ten nanometers) is produced by a single company (Taiwan Semiconductor Manufacturing Corporation or TSMC) in Taiwan, while the remaining 8 percent is produced in South Korea.[3] These are the most important advanced semiconductor chips. The concern here is about a specific relationship that plays out at a very granular level.

Smartphones are another example. In a recent paper, Thun and others (2022) introduce a new concept, "massive modularity," and claim that it adequately describes the nature of many products in technologically intensive industries, such as mobile handsets (i.e., smartphones). Massive modular ecosystems (MMEs) are comprised of several interconnected functional modules that can be broken down into more specialized modules, each with its own standards, innovation potential, and market structure. While the industry as a whole is fragmented and geographically dispersed, there is extremely high market concentration at the level of each component with production being concentrated in individual countries.

This is evident in figure 9 in Thun and others (2022). The manufacturing of a mobile phone requires components from multiple regions of the world: the United States, Europe, China, Japan, South Korea, Taiwan, and others. So, at the level of the product, that is, the mobile phone, there seems to be little concentration in individual countries. But at a more granular level, the figure reveals extremely high concentration at the component or subsystem level: the market for the display component, for example, is dominated by South Korea with an 81 percent market share. On the other hand, the market for the central processing unit is dominated by the United States with a 72 percent share.

There are two key takeaways from this figure in Thun and others (2022). First, given that for any specific component there is enormous concentration, there are good reasons to be concerned about dependency and resilience.

3. See Varas and others (2021, 35).

Second, for the final product to be manufactured, one needs the cooperation of all countries involved. This makes decoupling from any specific country extremely costly.

As a sidenote, this is precisely the reason that the United States has so much power in imposing export restrictions vis-à-vis China in the semiconductor market. The United States may not be manufacturing and exporting semiconductors directly to China anymore—the manufacturing takes place in foundries located in other countries. However, the United States is still extremely important in design, software development, and specialized capital equipment used by the foundries. As a result, the United States turns out to be as important to the semiconductor global supply chains as the countries in which the foundries are located (e.g., Taiwan).

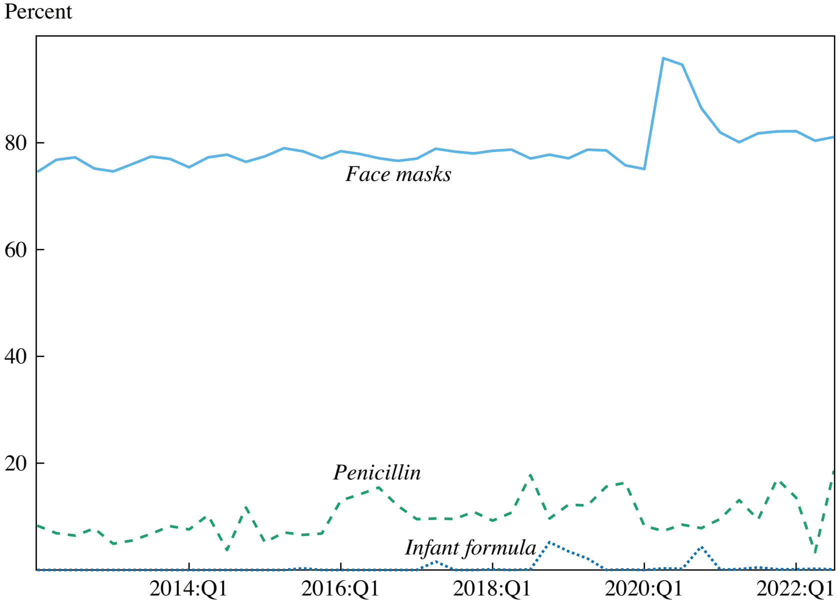
These patterns lead to the policy-related paradox eloquently described by Thun and others (2022) in the abstract of their paper: "MMEs generate strategic and geopolitical pressures for decoupling when placed under stress, but the same set of circumstances also creates pressures for maintaining the business relationships and institutions that have come to underpin global integration."

Let me now come back to a statement I made at the beginning of my discussion, namely that resilience cannot be evaluated without reference to a specific shock. Let us focus on those cases where the US dependency on China, as revealed by import shares or availability of alternative import sources, is high. As pointed out by Evenett (2020) and Goldberg and Reed (2023), such cases are rare. Figure 1 below reproduces the figure 7, panel A, of Goldberg and Reed (2023). It displays the share of US imports from non-friendly countries[4] for three critical products in the health care sector: penicillin, infant formula, and face masks. The shares of imports from non-friendly countries are minuscule for penicillin and infant formula. However, face masks follow a different pattern. Since 2012, almost 80 percent of imports of face masks come from a single non-friendly country, China. What does this imply for resilience?

The uptick in figure 1 during the second and third quarters of 2020 gives a hint at the answer. At the peak of the pandemic in the United States, imports of face masks from China increased substantially and helped alleviate domestic bottlenecks. Due to fortuitous circumstances, the first wave of COVID-19 was over in China by the time COVID-19 affected the

4. Countries are classified as non-friendly if, in the YouGov (2017) survey, less than 50 percent of Americans view the country as a friend or ally. See Goldberg and Reed (2023), notes to figure 7.

Figure 1. Percent of Imports of Medical Goods from Non-friendly Countries



Source: Reproduced from Goldberg and Reed (2023), copyright The Brookings Institution.

United States, and excess supplies of face masks in China were redirected toward the United States. This is a case where there was high dependency on China—as measured by the US import share. Nevertheless, this dependency proved beneficial during the pandemic and increased the resilience of the US economy.

Of course, the response of imports may be different in the future if we are faced with a different type of shock. But once again, the point is that resilience is not a meaningful concept without reference to the specific shock with respect to which resilience is evaluated.

The authors argue that systemic shocks are becoming more important. I am not sure what the evidence to that effect is. But even if this is the case, it is still unclear what the look-through measures imply for resilience.

I take systemic shocks in this context to mean shocks that affect multiple sectors of an economy, let's say China. If a country-specific shock hit a country as large as China, not only the United States, but the entire world would be affected. But what would such a shock plausibly be?

Broadly speaking, there are two types of shocks: natural shocks (e.g., earthquakes, tsunamis, weather-related events) that are exogenous to policy, at least in short-term horizons; and man-made shocks, such as shocks caused by shifting geopolitics.

A natural shock is unlikely to affect a country with the geographic size of China all at once. Even COVID-19, the largest shock we have recently experienced, affected China in waves, making it more manageable and containing its international trade ramifications. On the other hand, a man-made, policy-induced shock, triggered by geopolitical tensions, is highly likely.

Given the extent of international interdependence, any action taken by China or the United States in response to a geopolitical shock would require the cooperation of multiple trade partners to be effective—it would require "weaponized interdependence," to use the term coined by Farrell and Newman (2019). If, for instance, China decided to stop supplying the US market for geopolitical reasons, then it would have to persuade other countries, such as Vietnam, to also stop exporting to the United States—otherwise Chinese exports would reach the United States indirectly via Vietnam. And vice versa, if the United States wants to be effective in containing the exports of a particular product, such as advanced semiconductor chips, to China, it needs the cooperation of all countries involved in the semiconductor global value chain (as we have seen in the past year).

Such actions would reverberate through the world trading system with potentially severe long-run effects on international trade and prosperity. But in this case, the pain would be self-inflicted in my opinion. In the presence of a high degree of international interdependence, there are two ways to increase resilience to geopolitical risk. The first is to reduce interdependence, retreating to trade among "friends." The other is to try to avoid conflict in the first place by managing, not escalating, existing tensions. Rather than rallying as many countries as possible to make trade restrictions bite, we could be encouraging international cooperation as a means to increase resilience.

CONCLUDING REMARKS To conclude, the paper offers a valuable measurement exercise that will have useful applications in the evaluation of trade policy, especially the recent actions to decouple from China. From the perspective of resilience, it is important to lay out a clear conceptual framework before attempting to assess resilience. Most importantly, the data and measures provided in this study need to be complemented by case studies of individual sectors or products that will provide a deeper understanding of the complex technologies and interdependencies at a more granular level. I hope that the present paper will inspire such work in the future.

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COMMENT BY

YANN CALVÓ LÓPEZ and BENJAMIN GOLUB The COVID-19 pandemic reminded the world of the importance of supply chains and of their fragility. From the beginning of the pandemic in early 2020 and lasting beyond the end of 2021, shortages of consumer and intermediate goods became widespread across many locations and industries. Supply chain issues have been seen as a major driver of economic volatility and inflation in the United States, the eurozone, and beyond (Helper and Soltas 2021; De Santis and Stoevsky 2023; Rubene 2023; De Guindos 2023). Baldwin, Freeman, and Theodorakopoulos (henceforth "the authors") are motivated by the challenge of understanding the structural economic factors underlying these disruptions. The authors document the exposures of US manufacturing to various industries and locales, examine the various shocks that can travel via these exposures, and discuss policy remedies.

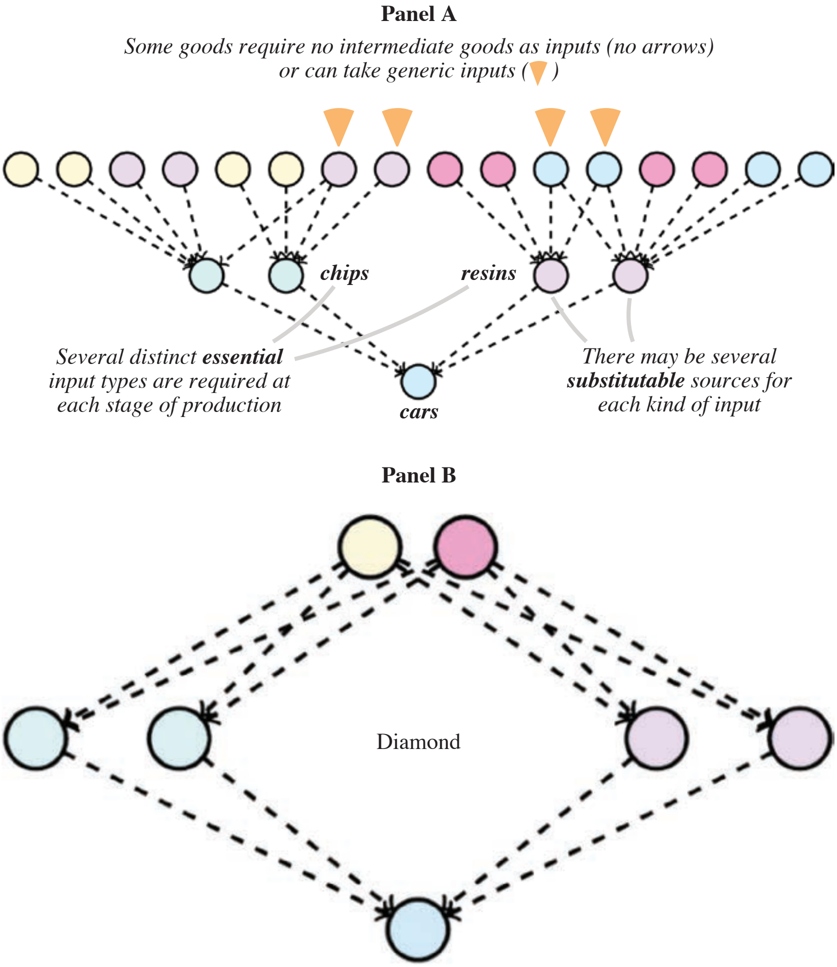
In this comment, we argue that microeconomic modeling of individual firms or plants, and their supply relationships, is essential to understanding supply chain volatility—even if the ultimate focus is macroeconomic.

To articulate this point, we first review an approach to modeling a supply network developed by Elliott, Golub, and Leduc (2022). A supply network consists of a set of firms (nodes) and sourcing relationships among them (directed links) reflecting who sources inputs from whom.[1] Input requirements can be generic or specific. Some firms can source generic inputs from a large variety of suppliers; others have customized inputs and can only get certain inputs if specific partners deliver on contracts. A firm's supply network can have many tiers—that is, a firm's suppliers may source goods from other suppliers further upstream, and so forth. In practice, looking even a few levels into such networks reveals a vast array of items and businesses, with dependencies that branch extensively—in contrast to the linear structure that is suggested by the term *supply chain*. To take a concrete example, after the Great East Japan Earthquake—a disruption whose consequences cascaded far beyond the northeast of Japan, where it started—Toyota mapped out its supply network, probing as many as ten layers of indirect dependence. This exercise uncovered 400,000 items that Toyota sources directly or indirectly (McLain 2021).[2] A schematic illustration of this kind of network is shown in figure 1, panel A.

1. In large firms, the nodes should be thought of as plants; we use the term *firms* in our exposition for simplicity.

2. Lund and others (2020) did a similar exercise for General Motors and found that it had over 17,000 indirect suppliers.

Figure 1. Firm-Level Supply Networks



Source: Authors' illustration.

Note: Panel A shows the main features of supply networks in our model: sourcing of multiple types of essential inputs by each firm (or plant); the possibility of multi-sourcing; and some nodes requiring no inputs or only generic inputs. The arrows are supply relationships. They indicate that a given firm can potentially supply an input to the firm downstream. Panel B shows an example of a diamond-shaped network. Despite the appearance of diversification in the first layer, the firm farthest downstream ultimately depends on a small group of suppliers.

The structure of a supply network describes exposures—direct and indirect—of firms to the performance of other firms. These exposures are the medium through which economic distress is transmitted from firm to firm. The ultimate source of distress is an economic shock—an exogenous disruption to some aspect of the network.

To give a sense of how such a perspective is useful, we provide some brief illustrations of supply network volatility, introducing some key aspects of both the networks and the types of disruptions they experience. Throughout this comment, we will mostly focus on discrete failures, such as a firm being unable to produce for a time, rather than a gradual degradation of performance.[3] Links may fail if relationships are disrupted—for example, by regulatory barriers to trade, failures of sourcing agreements, shipping congestion, or geopolitical conflicts. Nodes may fail when firms are temporarily unable to operate due, for example, to strikes, financing problems, or natural disasters.

Our first illustration focuses on the concentration of reliance, which occurs when a large amount of production ultimately depends on a small part of the economy—either a few firms or a specific locale. This can be seen as a diamond shape in the supply networks, as illustrated in figure 1, panel B: a firm's sourcing might look diversified through a few layers of dependence but narrows further upstream. In such a situation, regional disruptions, or even firm-specific ones, can have dramatic and distant consequences. For instance, a fire in a cleanroom at Renesas Electronics Corporation, a Japanese chip producer, contributed to a chip shortage that may have cost carmakers as much as $110 billion (Wayland 2021; Sourcengine Team 2021). Similarly, after the Great East Japan Earthquake, firms with disaster-hit suppliers experienced a 3.8 percentage point reduction in their growth rate, while firms with disaster-hit consumers experienced a 3.1 percentage point decline (Carvalho and others 2021). These results also highlight the importance of specific dependencies. Barrot and Sauvagnat (2016) find that, because of input specificity, it takes substantial time—often several months—for firms to substitute to new suppliers after idiosyncratic shocks, even when alternative sources are available. The disruptions we are interested in occur on this time scale: a supplier fails, their customers experience disruption, then that cascades to their customers, and so on.

3. The extensive literature in economics on so-called production networks, as surveyed, for example, in Carvalho and Tahbaz-Salehi (2019) and Baqaee and Rubbo (2023), typically models disruptions as continuous (i.e., sufficiently small, or at least well-modeled mathematically as being small) and uses calculus. Discrete disruptions are arguably more central to short-run supply network volatility.

Diamond-shaped dependencies are important, but they are only one of the ways that supply network structures can amplify vulnerability to shocks. Many recent supply network problems cannot be traced to cascades emanating from some salient point of failure. Baldwin, Freeman, and Theodorakopoulos offer a useful taxonomy of different kinds of shocks and then give the following sketch of the pandemic supply network crisis, highlighting a shock that is the polar opposite of an idiosyncratic shock to a firm. During the COVID-19 pandemic, there was a sudden increase in demand for consumer goods—for example, exercise machines and televisions—as consumers substituted away from in-person services to leisure at home. This spike in demand strained the global logistics system. Though it responded by shipping more goods than ever before (UNCTAD 2021), the resulting worldwide logistical issues, such as congested ports and misplaced shipping containers, had far-reaching effects. These had an impact on most shipping links, including many unrelated to the initial shock. The resulting widespread disruptions, correlated across many industries, became a central focus in the popular and business press. These disruptions constituted an aggregate shock to the links in the supply network. Our perspective is that understanding the implications of this phenomenon requires a firm-level model, combined with new insights in network theory. We will see that even well-diversified, complex networks can be very fragile in the face of aggregate shocks, starkly amplifying them (Elliott and Golub 2022), and that firm incentives can be severely misaligned with social welfare.

More broadly, we use the theoretical lens of supply networks to interrogate the facts and policy issues raised by the authors. We do this with reference to each of their main exercises: mapping exposures, modeling different kinds of shocks, and contemplating the endogenous responses of firms and policymakers. In each case, our perspective is that a model of firm-level supply networks is essential to making sense of the issues.

EXPOSURES: THE LIMITATIONS OF AGGREGATE STATISTICS The authors' main quantitative exercise is an accounting of how much various manufacturing sectors, in the United States and comparator countries, source from specific sectors in specific nations, both directly and indirectly. They primarily use input-output tables to report aggregated dependencies.[4] The discussion recounts the measurements and certain trends in them. The exercise is motivated by questions of exposure to disruptions, but the paper stops short of offering a model to make this connection precise. While we believe that the measurements are highly informative about aspects of supply networks

4. Specifically, the OECD's 2021 release of Inter-Country Input Output (ICIO) tables.

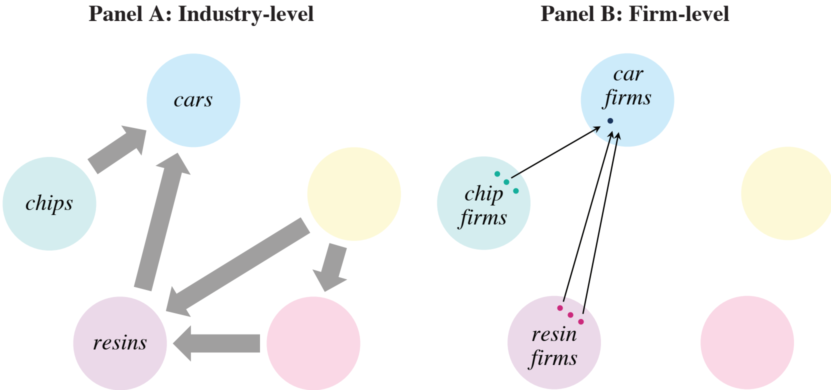
as we have defined them, they present some limitations. In this section, we interpret and critique the authors' discussion of dependencies.

Baldwin, Freeman, and Theodorakopoulos emphasize indirect exposure: for instance, an electronic component imported by the US auto industry from South Korea, constituting 15 percent of the dollar value of autos, might contain 50 percent Chinese inputs (in value terms). The paper uses the term *look-through exposure* to refer to the fraction of a sector's inputs sourced from a given industry in a given country when all indirect dependencies are accounted for. In the current example, the sourcing chain we have described would contribute 7.5 percent of US auto inputs to China. This may be contrasted with *face value exposure*, which only considers the immediate origin of intermediate inputs. Section II of the authors' paper quantifies the look-through exposures of various manufacturing sectors, revealing that these differ from, and often exceed, corresponding face value exposures. It also documents a geographic shift in look-through foreign intermediate dependencies, focusing on a concentration toward China between 1995 and 2018—the last year for which they have input-output data. More broadly, the paper contrasts the insights that can be derived from look-through exposure accounting as compared with a face value approach. It argues that the former allows for a more comprehensive picture of interdependencies than the latter.

The dynamics of exposure statistics at the industry-country level are fascinating and add much beyond the study of face value exposures. However, the dangers an economy faces due to disruptions are ultimately realized in the firm-level supply network. For this reason, our perspective is that, conceptually, the analysis must start at the disaggregated level, illustrated in figure 2, panel B. Moreover, the indirect exposures at the industry-country level are just one summary statistic of firm exposures. It is important to think through what such aggregated exposure statistics—whether face value or look-through—can and cannot tell us about how firms are affected by changes in their suppliers' functionality. In what follows, we point to several gaps between what the look-through statistics capture and what ultimately matters.

Industry-level indirect reliance can neglect across-industry substitution. The first concern with exposure accounting is that it can understate substitution possibilities, even in the short run. Across-industry substitution can play a pivotal role in avoiding catastrophic outcomes in the face of supply chain disruptions. To illustrate this, we focus on a case that Baldwin, Freeman, and Theodorakopoulos mention—that of Germany after the disruption of Russian gas supplies in the summer of 2022.

Figure 2. A Comparison of the Industry-Level versus Firm-Level Picture



Source: Authors' illustration.
Note: Panel A depicts input flows between industries. In the firm-level picture (shown in panel B), in contrast, a given firm (denoted by a small node) must use specific relationships to source from firms in other industries. Some of these links function in a given period, while others might not.

In March 2022, Russian gas accounted for around 55 percent of Germany's gas consumption. Citing reports that Germany was profoundly dependent on Russian gas, the German government did not sever ties with Russia following the start of the Russian invasion of Ukraine. Nonetheless, by the end of the summer of 2022, Germany stopped receiving Russian gas when Gazprom, the main Russian state-owned gas company, discontinued its supply. Surprisingly, Germany only experienced a "technical mini-recession" during the subsequent winter (Moll, Schularick, and Zachmann 2023, abstract). This outcome sharply diverged from some earlier forecasts, which had predicted a 6 to 12 percent drop in Germany's GDP in the event of a total embargo on Russian gas (Moll, Schularick, and Zachmann 2023).

In addition to some alternate sourcing (e.g., increased imports of liquefied natural gas), input substitution across energy sources was crucial in mitigating the impact of a shock of this type, as extensively documented by Moll, Schularick, and Zachmann (2023). The point here is a familiar one—that input-output tables are just a snapshot. The exposures documented might reflect rigid technological constraints that create a severe dependence, but they also might be easily bypassed when needed. In fact, there turned out to be firms that were already set up to source energy without Russian gas; these firms had the capacity to expand production, and orders could shift to them. These aspects of firm-level production structure were essential to Germany's surprising resilience.

Value-weighted exposure mapping understates firm-level vulnerability. While an industry-level exposure snapshot can understate substitution possibilities and the resilience of an economy, it can also understate important rigidities. As we have already mentioned, customization is a big part of how firms get their parts, and firms often fail to quickly find alternative suppliers when it is necessary (Barrot and Sauvagnat 2016). Moreover, as the just-cited paper emphasizes (building on a large body of literature), modern production involves strong complementarities in inputs: a missing part disables the productive use of many others.

These facts together imply that if a firm is missing a low-cost, low-value-added item, such as certain cheap microchips, major disruptions can ensue (Elliott and Jackson 2023). Such an item, however, would barely show up in the exposure statistics since these statistics are value-weighted at market prices. From the macroeconomic perspective, a cheap good cannot stop high-value production. But this perspective misses rigidities that are central to volatility on the timescale of several quarters. The fact that a firm can find another supplier of a disrupted input at a low price in three months does not render it operational now.[5]

Dangerous foreign reliance, or beneficial diversification? Behind the descriptive statistics in section II of the paper, an issue of seemingly obvious policy interest is the increased exposure of the United States and several similar economies to imports. As the authors note, whether such exposure is good or bad is unclear. We elaborate on this point here and put it in the context of our supply network perspective.

Let us focus, for concreteness, on the issue of US (direct and indirect) exposure to Chinese inputs. While "country" is a natural unit for accounting purposes, it is not clear that concentrated sourcing at the country level is concentrated in the ways that ultimately matter. Sourcing from a large country could potentially provide considerable robustness. In particular, conditional on sourcing many inputs from China, the extent of geographical concentration within China matters. If sourcing is narrowly focused on specific areas, then US production can be exposed to highly localized shocks. On the other hand, if sourcing is diversified within China, that could provide

5. Baldwin, Freeman, and Theodorakopoulos recognize the importance of disaggregating in studying exposures at the product level in section II.F. This analysis, however, is limited by available data. They use detailed export and import statistics published by the US Census Bureau, but these have two important limitations: they do not contain information on which sector imports the goods and do not distinguish between intermediate and final goods. Moreover, such data are informative only about face value exposure—they only consider the direct source of intermediate inputs.

considerable protection against idiosyncratic risk, though not against distinctively political or otherwise nationally correlated risks.

The takeaway is that the decision to carry out exposure mapping at a specific level, such as the country level, should be supported by an explicit account of why we worry about exposure at that particular level or at least why that level offers a reasonable proxy for the issue of interest.

A summary. The unifying message of this section is that look-through exposures should be seen as a summary statistic of a complex microeconomic reality underneath—that of the firm connections. Despite their usefulness in depicting possible sources of supply chain fragility, they offer only a partial accounting of many important features of supply networks. In the remainder of this comment, we discuss how exposure mapping can be used in conjunction with shock modeling to understand some salient supply network risks.

SHOCKS: THE SOURCES OF DISRUPTION To analyze how reliance shapes resilience and to design interventions, we must model the shocks or potential disruptions the network faces. Baldwin, Freeman, and Theodorakopoulos develop a very useful typology of supply chain shocks. Here, we review it and then discuss a particular aspect of it that we think deserves deeper theoretical and empirical study.

The authors classify shocks into three different sources:

- *Supply shocks* refer to events or situations that cause significant disruptions or disturbances in the availability or production of goods and services within a supply chain.
- *Demand shocks* refer to sudden and significant changes in demand for products and services that affect the supply chain.
- *Connectivity shocks* refer to significant disruptions or disturbances in the interconnected and interdependent networks that facilitate the movement of inputs within the supply chain.

They cross this classification with a division of shocks into two types:

- *Idiosyncratic*: These are firm-specific or otherwise highly localized disruptions that affect one supply chain, as opposed to broader, market-wide disturbances. They are typically unforeseen and can arise from internal or external factors specific to the firm's operations, relationships, or environment.
- *Systemic*: Systemic shocks are large-scale disruptions that affect multiple companies, industries, or even entire economies. These shocks are characterized by their widespread impact across the global supply chain network.

ZOOMING IN ON CONNECTIVITY Connectivity, from the first axis of the taxonomy, seems especially important to understanding the 2020–2022 shortages, as well as supply chain volatility more generally. Nevertheless, we see this concept as understudied relative to its importance.

Connectivity encompasses much more than just logistical links. Let us dig down into several dimensions of connectivity and the economic factors that determine it. The first dimension consists of technological relationships. The large-scale structure of the supply network depicted in figure 2, panel B, is shaped both by technological facts and by firms' choices of which of many possible "recipes" to use in producing goods (Boehm and Oberfield 2020). For example, a clothing manufacturer can have workers sew buttons onto clothing by hand or buy specialized machines for this purpose. Firms' choices here, in turn, are influenced by things like what kind of software is available to help them plan and integrate production across firms, and whether standards exist that help harmonize production processes. Another choice is multi-sourcing: how many alternative (potential) suppliers does a firm have access to for a certain input? A closely related but softer part of connectivity concerns relational contracts. In the face of potential disruptions, which can be very costly (Hendricks and Singhal 2003, 2005a, 2005b), firms invest in relationships. These investments include favors such as ordering in advance to assist a supplier during a period of low demand (Uzzi 1997) and the allocation of scarce supply to a customer in need (Carlton 1978). They also include a variety of noncontractible activities to stabilize and facilitate relationships; an important outcome of these activities is building interpersonal trust. Legal and contractual frameworks also play a significant role. They form a base for connectivity. Finally, there is the logistics and shipping aspect of connectivity, which is the most familiar: the systems and services that move goods from one place to another. These interact in obvious ways with the previous aspects.

Connectivity shocks correspondingly include a range of disruptions. An idiosyncratic shock to relational connectivity might consist of a contract breaking down due to debt nonpayment. Idiosyncratic logistical shocks include fires and misplaced shipping pallets.[6] On a broader scale, Brexit is an example of an aggregate shock to both relational contracts and the logistics network. Increased bureaucracy and changes in rules and regulations have made it difficult for many UK firms to deal with their EU counterparts (British Chambers of Commerce 2021). Similarly, an aggregate logistical

6. Hendricks and Singhal (2003, 2005a, 2005b) show that localized disruptions are often associated with durable declines in sales growth and stock returns.

shock can manifest as congestion at points of entry such as tunnels or ports, leading to delayed deliveries for many industries at once (Murray 2023; Komaromi, Cerdeiro, and Liu 2022).[7]

A conceptual challenge. The discussion above makes clear that one type of shock can lead to another. Demand shocks can lead to connectivity shocks. For instance, the demand shock during the COVID-19 pandemic led to a connectivity shock (port congestion, etc.). These shocks, in turn, seemed to seriously affect aggregate supply, motivating the theory of Elliott, Golub, and Leduc (2022). Including such effects in models is clearly important. However, such issues have not received much attention in standard macroeconomic models, and this presents an important challenge for researchers. Indeed, standard models do not even have a standard abstraction for capturing the object to which connectivity shocks happen. We might call this object *connectivity capital*. An adequate notion of connectivity capital should ultimately be rich enough to include the various dimensions discussed above.

It is worth remarking on the reason that we call connectivity a type of capital. We do this because many of its dimensions can be seen as produced factors of production that are not fully depleted in the course of particular production processes.[8]

RESPONSES TO SHOCKS: FIRM BEHAVIOR AND PUBLIC POLICY The consequences of shocks are a concern for firms as well as for policymakers at the subnational, national, and international levels. Both types of actors make many choices that affect both the structure of firm supply networks and the probability of shocks occurring. Their choices thus shape the robustness of the economy.

Firms' incentives in making these choices may be misaligned with the social interest in aggregate robustness. Indeed, Baldwin, Freeman, and Theodorakopoulos sketch some theoretical ideas concerning why the incentives of firms to mitigate risks might not be aligned with those of a social

7. Technological compatibility is rarely shocked in the short run, but in the longer run, advances in information technology, such as AutoCAD modeling and enterprise resource planning systems, have reshaped how firms interact.

8. Connectivity also relies on a variety of services and human capital inputs. It is tempting to take a minimal approach and incorporate connectivity as simply a complement to shipping services. At a minimum, this would have to be done in a modern production network model (Baqaee and Farhi 2019, 2020), since in the old-school models, Hulten's theorem applies and the quantitative estimates of the harm of negative shipping shocks seem severely understated (because shipping value added at usual prices is low). But beyond this, connectivity shocks can be amplified in distinctive ways—an issue studied by Elliott, Golub, and Leduc (2022) and Acemoglu and Tahbaz-Salehi (2023).

planner.[9] They argue that firms might invest less in robustness than is socially optimal because they are less risk-averse than a planner. Our view is that this perspective is insufficiently precise for understanding the issues distinctive to supply chain risk. The basic premise is not even generally true: a social planner is often much less risk-averse over the fortunes of any given firm than individual firm decision-makers, because small firms make only a small relative contribution to aggregate outcomes. What is true is that social planners are more risk-averse over disasters where many firms fail at once, or where supply is severely disrupted. But then what is key is whether firms fail in a correlated way, and understanding that requires more detailed modeling.

The supply network perspective provides an organizing framework. To make this point, we focus particularly on connectivity shocks, though the analysis extends to other types of shocks. Misalignment of incentives arises in all of the various chosen aspects of connectivity we have emphasized above—firms' choices of inputs and multi-sourcing, as well as their management of relational contracts and logistics. We now analyze these misalignments, bringing the above-discussed typology of shocks together with a firm-level approach to exposure mapping.

Decisions about suppliers. Perhaps the most fundamental connectivity decisions made in the economy are firms' sourcing decisions. These have large consequences from the standpoint of robustness. For example, if a firm ends up having high indirect dependence on a single region, it might end up highly vulnerable to regional supply or logistics shocks.

Firms' incentives in making these decisions need not be aligned with those of a planner. For example, in choosing their suppliers, many firms might prefer to source from a single region because of economies of scale and scope in setting up sourcing relationships. Moreover, and probably more importantly, the lowest-cost suppliers, with the highest short-run productivity, might all be located in one region, for example, to benefit from agglomeration externalities (Duranton and Puga 2004; Rosenthal and Strange 2004). Even in the absence of colocation of a firm's immediate suppliers, a more dispersed set of suppliers might rely on the same upstream providers (as in the diamond-shaped network example discussed earlier). In either case, a single regional shock could simultaneously disrupt many

9. We use the construct, familiar in economic theory, of a fictitious entity—the social planner—that makes decisions aimed at maximizing some notion of social surplus. This construct is helpful for understanding distortions that cause individual decisions to differ from what such a planner would do.

firms that have arranged their sourcing this way, resulting in widespread fragility across the supply network.

The key tension between individual and social interests is that the planner is concerned with the correlation of firms' performance, whereas each individual firm is concerned only with its own performance and profitability. Whether this is a problem or not depends on whether firms' sourcing incentives push their performance to become highly correlated.

How much to invest in a given link's robustness. Beyond choosing whom to link with, firms invest in making links with their suppliers more robust and resilient. They might, for instance, invest in their logistics departments —for instance, by using technologies to monitor shipments and communicate about disruptions. They can also store more inventory (so as to compensate for temporary disruptions by having extra inputs on hand).[10] Finally, they can undertake investments in their relationships by optimizing both relational and formal contracts.

Such investments protect firms against shocks to the performance of their relationships. In other words, these investments are especially suited to safeguard firms against connectivity shocks. However, as Elliott, Golub, and Leduc (2022) show, there are circumstances in which firms have too little incentive to invest in relationship strength, compared to what is socially optimal.

To make this point, Elliott, Golub, and Leduc (2022) work with a version of the supply network model sketched earlier in this comment. In the model, each firm can invest in robustness and thereby improve its relationship strengths, defined as the probability that each relationship will be functional in a given time period. They give conditions under which it is optimal for firms to invest less in robustness than what would be socially optimal. This leads to inefficient supply chain vulnerabilities: the economy has a substantial probability of ending up in a configuration where small, systemic shocks affecting the functioning of supply relationships have stark, amplifying effects.[11] A planner controlling link investments, on the

10. The management of inventory has been an important concern in the field of operations. Running a "just-in-time" strategy with low inventories reduces costs (Callen, Fader, and Krinsky 2000). Keeping more inventory allows firms to weather logistical shocks better. But when a firm sources a large number of complex inputs, customized to evolving production, managing risk through inventory can become impractical (Goodman and Chokshi 2021).

11. A key condition for this result to hold is the widespread customization of intermediate inputs or, in other words, a lack of short-run substitution. As previously mentioned, there is good evidence that firms do indeed struggle to substitute for new suppliers in the timescale of one or two quarters (Barrot and Sauvagnat 2016).

other hand, would never choose to make the economy vulnerable to such fragility.

Summing up. A reliable instinct of academic economists is to imagine a certain fictitious complete-markets benchmark in order to illuminate what missing market is preventing the efficient allocation of resources. In our setting, the complete-market benchmark would entail the existence of securities allowing bets on every conceivable event (e.g., every possible pattern of shocks), along with some additional assumptions, for example, that the mathematical descriptions of firms' production possibilities are sufficiently well-behaved. In such a paradise, market equilibria would exist in which all risk would be correctly priced, and social interests in firms' reliability could be transmitted to them via the price mechanism.

Such markets do not and probably could not exist due to the sheer vastness of vagueness of the space of possible shocks. It is a natural theoretical question whether markets that are somewhat more realistic could mitigate incentive misalignment. For example, could incentives be improved by dynamic markets where firms that survive are allowed to gouge their customers to some extent? We are not optimistic that this would offer a robust solution.[12]

What is clear is that the investments firms endogenously make toward robustness generally differ from what is socially optimal. A firm-level analysis is important for revealing both this divergence and the factors driving it. And within that type of analysis, we argue that connectivity capital and shocks to it are likely to play an outsized yet understudied role. In the next section, we make one more argument for that position, using a policy issue that motivates Baldwin, Freeman, and Theodorakopoulos.

WHY FEAR EXPOSURE TO CHINA? Baldwin, Freeman, and Theodorakopoulos are clearly interested in exposure to countries—with China playing a particularly central role due to its rise as an important indirect supplier. We have emphasized that the right network to focus on is at the firm level. And we have also noted that, at this level, it is not obvious why country-level exposures are especially significant. For instance, a large country such as China might offer unusually good opportunities for multi-sourcing and, for US firms, additionally provide insurance against domestic shocks.

It seems clear that concern over reliance on Chinese inputs must stem from the anticipation of country-level shocks to commercial relationships that Chinese firms have with their counterparties. Such shocks could arise from tariffs or geopolitical and military tensions. However, even once we

12. See Elliott and Golub (2022) for a fuller discussion.

focus on such shocks, it still needs to be explained why US economic policymakers should be especially worried about the extent of *indirect* exposure to China. After all, it seems implausible that China would, or could, prevent the use of any of its inputs indirectly in US goods. For example, Russian energy remains an input into a great deal of production by countries sanctioning Russia after its 2022 full-scale invasion of Ukraine, while Russia indirectly buys many goods made in the European Union and the United States—including ones that are banned from directly buying.

The perspective of connectivity capital introduced above can nevertheless help rationalize concerns about exposure to China. The example of Brexit helps motivate the point. Brexit disrupted trade relations and the workings of commerce—by increasing regulatory hurdles, for example. The resulting effects have been widely discussed as a damper on European and UK trade and economic performance.[13] While the US relationship with China is much more arm's-length than the pre-Brexit relationship between Europe and the United Kingdom, increasing tension with China could have similar adverse consequences, degrading the performance of many links, including those between China and various non-US economies that supply the United States. Systemic damage to commerce within Asia and across the Pacific would be one of the main ways a China-related crisis would have an impact on supply networks.

The most natural way to view this is as a connectivity shock to many supply networks. We have discussed above the distinctive and severe ways in which these can be amplified. Properly describing these connectivity shocks in economic models and explaining why and how we should be concerned about them (beyond the rough sketch we have given) requires further developing our understanding, both theoretical and empirical, of supply networks. What is clear is that documenting growing indirect exposure is just a first step.

CONCLUDING DISCUSSION Our main message is that modeling of supply networks at the firm level is indispensable to understanding supply-chain volatility, even when the overarching focus is macroeconomic. Most of the interesting questions about supply chains and indirect exposures cannot be usefully analyzed while staying at a highly aggregated level.

We started by reviewing the authors' exposure mapping, discussing both its usefulness and aspects of exposure that are not captured by it—ones that require a firm-level analysis. We then reviewed and extended their

13. Office for Budget Responsibility, "Brexit Analysis," https://obr.uk/forecasts-in-depth/the-economy-forecast/brexit-analysis/.

typology of supply chain shocks, emphasizing the need for proper modeling of connectivity capital—the (multidimensional) object that is degraded when connectivity shocks happen. Next, we turned to a discussion of misalignments between firms and a social planner in incentives to invest in connectivity. Finally, we circled back to a focal policy concern of Baldwin, Freeman, and Theodorakopoulos: the dependence of the United States on Chinese intermediate inputs. We argued that the perspective of supply networks and their connectivity shocks is critical to making sense of why this may merit concern.

Broadly, the authors make clear the importance of supply network issues in understanding current economic trends. We have argued that these issues raise an urgent need for better concepts and theories of firm-level sourcing relationships and their disruptions. This poses an important challenge at the intersection of network theory and macroeconomics, which we hope will prove energizing to researchers.

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GENERAL DISCUSSION Şebnem Kalemli-Özcan emphasized the importance of timing in understanding macroeconomic dynamics, providing the example that goods that are considered substitutable in the long run may not be substitutable over the course of a few quarters, ultimately having an impact on macroeconomic aggregates such as inflation. She asked whether economists should be utilizing more micro-level to macro-level analysis to better understand macroeconomic indicators and dynamics like inflation and unemployment.

Georg Zachmann inquired whether the heterogeneity of companies that are users of inputs should be more strongly considered when measuring the impact of political shocks on the aggregate economy. Zachmann explained that companies can vary greatly in their productivity for a given input, and a shock to this input could result in the loss of further production from low value-added producers. He noted that this would decrease input consumption but leave a significant share of the value-added unaffected, creating a buffer against a supply crisis.

Elaine Buckberg emphasized that the private sector is not monolithic in its supply chain management strategies, such as multiple sourcing or inventory management, which play an important role in maintaining a competitive advantage. Buckberg stressed the importance of considering the duration of shocks, highlighting that the ability to endure a shock is more important than just its source.

Rebecca Freeman agreed that a distinction between the duration of shocks versus their source needs to be made. She noted that her coauthors and she tried to address this by creating a distinction between resilience and robustness—where resilience is the speed of recovery after a crisis, while robustness is related to where, and in which areas, failure is not acceptable.

Angelos Theodorakopoulos touched on the discussions of time horizon and heterogeneity by bringing up Pinelopi Goldberg's discussant remarks regarding the need to define resilience and exposure metrics, in addition to benchmarks, before making progress on measurement. Theodorakopoulos also drew attention to comments about large firms' relationships with their suppliers, pointing out that on the aggregate level, countries and industries are dependent upon a whole network of supply that should also be considered when thinking about trade exposure.

Tarek Hassan drew attention to the challenges of shock modeling and the potential value of quarterly data from firm executives' reports to financial markets. Hassan noted that by analyzing earnings calls, he was able to monitor the impact of business supply shocks and the propagation through final goods manufacturers, consumer durables, and industrials during the COVID-19 pandemic.

David Romer expressed his confusion regarding gross trade flow measures. He presented a hypothetical scenario where authors exchanged hundreds of versions of a paper via email across international borders, with each version differing only trivially from the previous one, and where a simple analysis based on gross trade flows would lead to the obviously incorrect conclusion that these flows increased the paper's value by several hundredfold. He argued that having clear objectives in designing trade metrics is important for work in this field, though he noted he was unsure of what exactly these measures might look like.

John Haltiwanger raised concerns about the timeliness of the input-output (IO) data, noting that Bureau of Economic Analysis had released comprehensive revisions to GDP accounts that day (September 28, 2023).[1] He stated that this was the first time the 2017 Economic Census had been used for the GDP accounts, noting that the reference year was 2012 until these revisions. Haltiwanger expressed concern about the data being too old and wondered if there were potential solutions or improvements to address the timeliness problem in the data.

Freeman agreed with points made about the coarseness and timeliness of the IO data, pointing out that the international organizations and academic institutions responsible for curating the data need to do lots of time-consuming preprocessing, on top of the fact that countries report data at different points in time. Freeman highlighted that one of the main advantages of the measure that they propose in their work is to create a more macroscopic view of differences between face value trade and look-through exposure. She noted that the IO data also allowed the authors to circumvent two important caveats regarding data at the product level used for analyses of the US economy and automotive sector. Freeman explained that the product-level data do not include which sector is importing a given good nor whether the good is an intermediate or final good—which are critical pieces of information for analyses. Freeman remarked that the trends they observed have been steady over time, which can serve as a benchmark when considering some of the timeliness issues.

Richard Baldwin responded to concerns about some of the caveats surrounding IO analyses, such as the lack of substitution in a Leontief production function, recognizing that these are important considerations to account for when interpreting the authors' findings. Baldwin noted that a single measure, such as Leontief inverse, does not necessarily summarize

1. Bureau of Economic Analysis, "Gross Domestic Product (Third Estimate), Corporate Profits (Revised Estimate), Second Quarter 2023 and Comprehensive Update," https://www.bea.gov/news/2023/gross-domestic-product-third-estimate-corporate-profits-revised-estimate-second-quarter.

all matrix information. He continued, mentioning that it would be worth analyzing the exact shape of trade networks to gain insights into fragilities and single points of failure. Baldwin also stated that he believed a computable general equilibrium would be necessary to provide advancements on the authors' analysis, particularly when allowing for substitutability between geographic origins and between products. He cautioned, however, that a model of this size can become too complex to intuitively understand. Baldwin noted that he thinks of their measures as a first-order approximation that can identify areas of dependencies worth further investigating for risk, while cautioning against directly interpreting dependencies as risk.

Romer asked whether an analysis focusing on market failures would in fact lead to the conclusion that an unregulated market results in insufficient resilience. He stated that while there is of course pervasive imperfect competition, he did not see this as obviously leading to an economy that is systematically less resilient than is socially optimal. He presented the example of a company like Airbus being concerned about preserving monopoly rents, which could lead to greater supply chain resiliency relative to what a social planner would choose. Romer concluded that before policymakers potentially intervene to increase resilience, there is a need for greater attention to the relevant basic microeconomic theory.

Jason Furman wondered whether the government taking an interest in resilience can lead to perverse incentives and greater risk-taking from private firms as a result. Furman emphasized the importance of understanding the cases in which the government interest in resilience will move firms down the risk-reward curve, to less supply chain risk exposure, in addition to the cases in which intervention will possibly have the opposite effect.

Wendy Edelberg presented her working hypothesis on the need for policy interventions to enhance firms' resilience. First, Edelberg noted that the emergence of relatively new and increasing risks from geopolitical and climate-related factors necessitates additional resilience. Second, she drew attention to managerial incentives, pointing out that during good times, managers tend to underinsure their firms because they are penalized for performing worse than their peers. Edelberg highlighted that during aggregate shocks, underinsuring is also incentivized as managers are not particularly penalized for poor performance, further supporting the need for additional policy measures.

Henry Aaron brought up inventories as a way to manage risk, stating that they should be possible to implement in large swaths of the economy, despite potentially being costly. Aaron pointed out that the private sector's calculations about the value of inventories may underestimate their social value, presenting a possible basis for government intervention to encourage more inventory holding. He stressed the need for empirical research to better understand the costs associated with carrying inventories across the manufacturing and industrial spectrum.

Baldwin thanked discussant Benjamin Golub for drawing attention to the fundamental source of shocks and noted that differentiating between supply, demand, and connectivity shocks can be useful when tailoring policy responses to different shocks. Baldwin provided the example of stockholding, stating that the policy is resilient to all three kinds of shocks. He noted that various countries have adopted stockholding in some form, citing the Strategic Petroleum Reserve and the Swiss government's subsidization of retailer stockholding in named products. Baldwin contrasted stockholding with geo-diversification, which he explained only works in supply shocks and not demand shocks. He highlighted that greater domestic production to reduce risk may even have the opposite effect, depending on the shock source. Baldwin agreed with Golub, stating that assessing a policy's cost and benefits before action is essential.

Iván Werning stated that if geopolitical risk is at the core of this work, it would be interesting to perform an analysis from the perspective of China to determine their supply chain dependence and resilience. Werning drew attention to the difference between mutual and one-sided trade dependence, noting that this could change the thinking about US-China trade relations.

Hoyt Bleakley contrasted the authors' findings with Mainland China a generation ago, hypothesizing that the direct and look-through exposure measures would have been close to zero then. To him, this suggested that the long-term elasticity of substitution might be high, which would mean long-term policies like de-Chinafication—that is, policies reducing US dependence on China—could be easier to implement.

Martin Baily commented that he believed that a large degree of supply chain difficulties during the COVID-19 pandemic were due to a significant shift in demand from services to goods, recognizing that the production issues in China also played an important role. Baily said previously he had thought that China's low value-added exports were not a major concern because the value-added was lower than the gross trade. He had reconsidered this, given the authors' analysis of look-through exposure, stating that China's assembly power could grant them significant influence as they are the last producer of a finished item. Baily also said the authors' work made him reconsider the value of single-supplier models, such as vertical keiretsu, that form close relationships with suppliers to improve quality and productivity. Baily noted that while it might be acceptable to maintain close single-supplier relationships for domestic supply, the benefits of multiple suppliers may outweigh the drawbacks when considering supply shocks and trade stability.

Robert Gordon drew attention to the rapid rise in China's prominence as a producer of finished and intermediate manufactured goods as well as the near zero growth in US manufacturing productivity over roughly the past decade.[2] Gordon expressed that he did not see a connection between Chinese intermediate imports and the lack of US productivity. He stated that, like Baily, he would have expected Chinese imports to be skewed toward lower value-added products, thus replacing US firms that produced low-value goods. This loss in low-productivity firms should theoretically have led to higher productivity in manufacturing, the absence of which puzzled Gordon.

Freeman touched on the asymmetric role of China in global supply chains, highlighting a companion paper in which they found that all major manufacturing countries are highly dependent on China—sourcing at least 2 percent of their total domestic and foreign inputs from China.[3] Freeman pointed out that China's role has declined because, although it has built up its industrial bases, becoming a major world supplier of industrial inputs, it is increasingly sourcing those inputs in its own economy domestically.

2. US Bureau of Labor Statistics, "Manufacturing Sector: Real Sectoral Output for All Workers [PRS30006041]," retrieved from FRED.

3. Richard Baldwin, Rebecca Freeman, and Angelos Theodorakopoulos, "Horses for Courses: Measuring Foreign Supply Chain Exposure," working paper 30525 (Cambridge, Mass.: National Bureau of Economic Research, 2022), https://www.nber.org/papers/w30525.

Online appendices

Appendix I: Face Value Exposure

This appendix presents the face value exposure equivalent of Figure 2.3.

Figure A1: Face Value Exposure of U.S. Sectors to Foreign Manufacturing Intermediate Inputs (%), 2018

	Vehicles	Machinery nec	Basic metals	Elec. Eq.	Oth. Transp. Eq.	Clothes	Fab. metal gds	Plastics	Oth. Manuf.	Wood	Chemical gds	Pharma	Paper gds	Electronics	Oth. non-metal gds	Food	Ref'd Petrol.	Manuf. avg.
China	1.2	1.5	.7	1.8	1.2	2	.8	1	1.2	.9	.7	.4	.8	1.5	.8	.3	0	1
Canada	1.1	.7	1.5	.9	.6	.3	.9	.5	.5	.9	.4	.2	.7	.2	.3	.3	.1	.6
Mexico	2	1.1	.9	1.1	.7	.3	.7	.3	.5	.3	.3	.1	.3	.6	.3	.2	0	.6
Japan	.9	.5	.3	.3	.5	.1	.2	.2	.2	.1	.2	.1	.1	.2	.1	.1	0	.2
Germany	.6	.5	.4	.3	.3	.2	.3	.3	.2	.1	.3	.4	.2	.1	.1	.1	0	.3
Korea	.4	.3	.2	.3	.2	.1	.2	.2	.1	.1	.2	.1	.1	.2	.1	0	0	.2
India	.1	.1	.1	.1	.1	.5	.1	.2	.2	.1	.1	.3	.1	0	.1	.1	0	.1
Taiwan	.1	.1	.1	.1	.2	.1	.1	.1	.1	0	.1	0	.1	.1	0	0	0	.1
Italy	.2	.2	.1	.1	.2	.1	.1	.1	.1	.1	.1	.1	.1	0	.1	0	0	.1
Brazil	.1	.1	.3	.1	.2	0	.2	.1	.1	.1	.1	0	.1	0	.1	0	0	.1
Ireland	0	0	0	0	0	.1	0	.2	.1	0	.2	1.6	.1	0	0	0	0	.2
France	.1	.1	.1	.1	.5	.1	.1	.1	.1	.1	.1	.1	.1	0	.1	0	0	.1
Russia	0	.1	.3	.1	.1	0	.2	.1	0	0	.1	0	0	0	0	0	.1	.1
UK	.2	.1	0	0	.2	0	0	.1	0	0	.1	.2	.1	0	0	0	0	.1
Switzerland	0	.1	0	.1	.1	0	0	.1	0	0	.1	.7	0	.1	0	0	0	.1
RoW	.9	1	1.5	1.2	1	1.1	1.1	.9	.9	.7	.8	1.1	.7	.6	.5	.5	.1	.9
Foreign	8.1	6.6	6.6	6.6	6	5.2	5.2	4.3	4.3	3.5	3.8	5.4	3.5	3.8	2.7	1.9	.5	4.6
USA	67.8	75.8	74.6	77.6	76.8	79.8	78	79.9	83	81.1	81.8	85.8	81.4	88.3	85.6	82.1	88.3	80.5

Source: Authors' elaboration based on 2021 OECD ICIO tables. Note: The numerator of the face value exposure is the technical coefficients of the **A** matrix, as described in Appendix II. In order to ease comparison with Figure 2.3, this is normalized with total manufactured intermediates across all sources (foreign and domestic) on a look-through basis. RoW stands for Rest of the World. Foreign is the sum of all foreign sources.

Appendix II: Mapping the 3-levels of answers to face value and look through measures

To be more precise about the distinction between face value and look through measures of exposure, we dig into the bit of matrix algebra we glossed over in the main text. In matrix form, the gross output of sectors (all sectors in all nations) are listed in a vector called $\mathbf{X}$. Each sector's gross output is either used for final demand, which we capture with the vector $\mathbf{F}$, or used as intermediate inputs, which we refer to as the matrix $\mathbf{T}$, that is $\mathbf{X} = \mathbf{T}\boldsymbol{\iota} + \mathbf{F}$, where $\boldsymbol{\iota}$ is a vector of 1s for aggregation of inputs into vector form. This is an accounting identity as it is merely categorizing the output of sectors into final or intermediate usage. The intermediate sales to any sector, in turn, are related to the gross production of all sectors, and the technical input-requirement matrix, defined as each element of $\mathbf{T}$ divided by the corresponding country-sector-specific gross output is denoted as $\mathbf{A}$. The $\mathbf{A}$ tells us how much intermediate inputs a single unit in a nation, say the U.S. auto sector, needs from any other sector, say the rubber sector in Brazil. In symbols, $\mathbf{T\iota} = \mathbf{AX}$. Putting together the pieces, $\mathbf{X} = \mathbf{T\iota} + \mathbf{F}$ can be written as $\mathbf{X} = \mathbf{AX} + \mathbf{F}$. Inverting, $\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-\mathbf{1}}\mathbf{F}$ where $\mathbf{I}$ is the identity matrix. Here, $(\mathbf{I} - \mathbf{A})^{-\mathbf{1}}$ is the famous Leontief matrix, more formally known as the Leontief inverse matrix.

Readers versed in matrix algebra will recognize that $(\mathbf{I} - \mathbf{A})^{-\mathbf{1}}$ equals the sum of an infinite series. The series is: $\mathbf{I} + \mathbf{A} + \mathbf{A}(\mathbf{A}) + \mathbf{A}(\mathbf{AA}) + \dots$. In words, the $\mathbf{I}$ is the first-level answer that reflects the production location. The term $\mathbf{A}$ reflects the second-level answer which captures the location of production of the inputs to the final good. The third level answer includes the inputs to the inputs, namely, $\mathbf{A}(\mathbf{A})$, $\mathbf{A}(\mathbf{AA})$, and so on.

In our terminology, the face value exposure is $\mathbf{I} + \mathbf{A}$ (i.e., the second-level answer) and the look through exposure is $(\mathbf{I} - \mathbf{A})^{-\mathbf{1}}$, (i.e., the third-level answer).

Appendix III. How Firms Manage the Risks

This appendix reviews another way of gauging whether supply chain shocks will continue. Namely, that is to look at the behavior of the economic actors who are closest to the problems: firms that manage extensive supply chains. Here we review some of the key recent firm-level adjustments undertaken as firms revamp their approaches to sourcing inputs and producing output.[1] There is no database on adjustments that firms are making in response to recent supply chain events, but the importance of the issue has led several organizations to undertake surveys that reveal important trends. The McKinsey Global Institute (MGI), for example, surveyed over 100 supply chain

[1] Initiatives to support supply chain resilience are also being undertaken at the intra- and inter-country level. For instance, on 31 May 2023, 14 partners of the Indo-Pacific Economic Framework for Prosperity (IPEF) concluded negotiations on a Supply Chain Agreement aimed at "increasing the resilience, efficiency, productivity, sustainability, transparency, diversification, security, fairness, and inclusivity of their supply chains" (U.S. Department of Commerce 2023). To achieve this aim, the IPEF has established three bodies. The Supply Chain Council will develop sector-specific action plans for critical sectors and key goods. The Supply Chain Response Network will establish an emergency communications channel for partners to seek support during supply chain disruptions/facilitate information sharing during a crisis. The Labor Rights Advisory board will support the promotion of labor rights throughout IPEF members' supply chains.

managers across various industries (MGI 2022). The survey results showed that 90% of respondents aimed to further increase resilience, and almost three-quarters of them planned to spend more on pro-resilience initiatives.

The most common change in supply chain risk management involved a rise in the level of inventories of inputs and final goods (80% increased inventories in 2022). Diversification of suppliers was almost as popular. Over 80% of respondents switched to dual sourcing. A trend towards shortening distances was also common. The survey for 2022 reported that 44% of firms were regionalizing their supply networks to counter disruptions. This was an increase from the 25% figure reported in the survey for 2021. Improving the transparency of supply chains was an important part of resiliency efforts, with 67% of respondents saying they set up digital dashboards to provide information on their supply chains. Likewise, the survey found that most companies invested more in digital supply chain management tools to allow them to plan better and react to shocks. The measures were reported as working. More than 83% of the firms stated that their new resilience tactics helped them minimize the impact of 2022 supply chain disruptions.

A second set of insights into firms' current adaptations comes from the World Economic Forum's "Resiliency Compass" (WEF 2021). The analytic framework synthesizes contributions from over 400 supply chain experts spanning the corporate, governmental, and academic sectors. As such, the compass serves as an indicative representation of how the private sector is strategically approaching and mitigating supply chain shocks. The Compass has eight 'compass points' grouped into demand-, supply-, and logistic-oriented.

The first strategy suggests that firms adopt a simplified product portfolio, thereby affording companies the capacity to substitute components and adapt production methodologies when encountering obstacles. The second strategy recommends a customer-centric orientation, utilizing technological advances to integrate consumer preferences into the product design stage. In terms of adaptability, adaptive information systems allow firms to recalibrate manufacturing schedules to accommodate evolving customer requirements. It also helps to anticipate demand shocks. These are the main recommendations on the demand side.

The third compass point emphasizes the critical need for transparency with respect to the financial viability of suppliers all along the supply chain. The goal here is to anticipate shocks emanating from firm-level bankruptcies or financial turmoil. The fourth strategic dimension focuses on fostering a diversified customer distribution network. Here the objective is to establish a distribution infrastructure with sufficient versatility to meet demand through multiple avenues, encompassing wholesalers, retailers, and digital sales channels. These are supply-side strategies; the next strategy addresses shocks that may arise from the connectivity links in the supply chain.

The fifth recommendation prescribes the establishment of agile and transparent logistics systems, enhancing visibility, control, and coordination across the supply chain by means of collaborative engagement with logistics partners. The subsequent strategy accentuates the centrality of manufacturing adaptability, advocating for a resiliently designed production network with an emphasis on flexibility in both locational and product aspects. The seventh strategy encourages a balanced approach to supplier diversity, harmonizing the need for risk mitigation with the imperatives of forming strategic partnerships with key suppliers. The last compass point underscores the necessity for advanced planning methodologies, promoting investments in emergent technologies and analytical tools to enable real-time responsiveness to market shifts in both supply and demand across the entire operational continuum.

A third notable contribution to the MGI and WEF findings is from the Deloitte 'Supply Chain Pulse Check' survey described above (Deloitte 2023). Importantly, the survey results in terms of measures that German companies are either currently implementing or have in their strategic planning to enhance supply chain resilience exhibit a high degree of concordance with those of the MGI survey. Specifically, the report finds that respondents are augmenting inventory levels and embracing additional logistical routes to mitigate the disruptions presently affecting supply chains. A notable 43% have already initiated these tactics, while an additional fifth are in the preparatory stages. Moreover, 38% of respondents are actively working to diversify their supplier base.

Taken together, the evidence from these surveys clearly suggests that firms do not believe that supply chain disruptions are a thing of the past.

Appendix IV. The 17 manufacturing sectors in the OECD ICIO tables

This appendix presents additional detail on what underlies the sectoral breakdown in the OECD ICIO data. Behind each broad manufacturing industry is aggregated data from detailed product-level trade data. Most categories consist of hundreds of detailed (6-digit) products, carefully mapped to ICIO broad sectors. While some are straightforward—like Vehicles or Clothes—others are more obscure. Other Non-Metal Goods, for example, includes products like glass and ceramic products as well as building materials like bricks and cement. The Wood sector includes various types of wood (oak, beech, maple, etc.) used for fuel, chips, sawdust, and tramway/railway sleepers. It also has wood flooring panels, corks, stoppers, wickerwork, etc. The Electronics sector covers around 270 products, from printing machines to pacemakers. This includes telephones, microphones, loudspeakers, headphones, amplifiers, sound recording devices, radar apparatus, valves, tubes, cameras, navigational instruments, medical appliances, and more.

Turning to the "not elsewhere included" (nec) categories: Machinery nec has 464 products, like chains, engines, pumps, compressors, fans, air conditioners, cranes, machines for printing, textiles, metalworking, and parts such as valves and bearings. Manufacturing nec has nearly 200 items divided into three categories: i) seemingly unrelated items like candles, lighters, and umbrellas; ii) precious materials and jewelry items like diamonds and pearls; and iii) musical instruments, games, and sports equipment. For a full mapping of disaggregate products to ICIO sectors see the OECD Bilateral Trade in Goods by Industry and End-use Category (BTDIxE) conversion key (http://oe.cd/btd).

Reference:

US Department of Commerce. 2023. "Press Statement on the Substantial Conclusion of IPEF Supply Chain Agreement Negotiations." Press release, May 27. https://www.commerce.gov/news/press-releases/2023/05/press-statement-substantial-conclusion-ipef-supply-chain-agreement.