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.

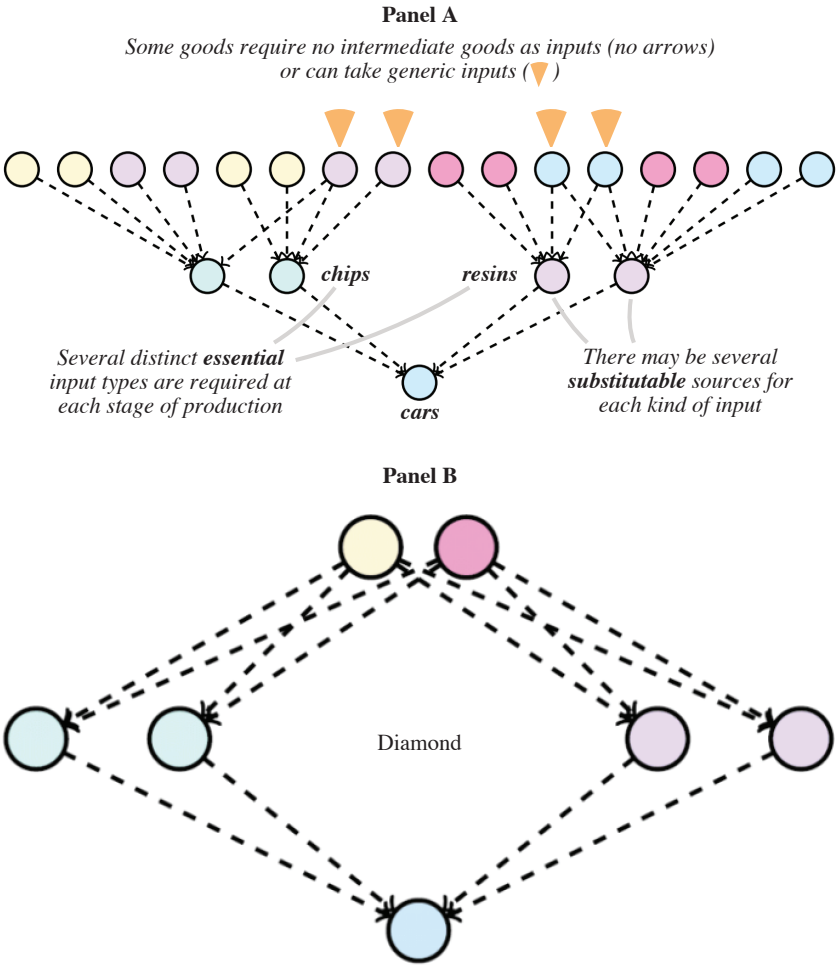
In this comment, we argue that microeconomic modeling of individual firms or plants, and their supply relationships, is essential to understanding supply chain volatility—even if the ultimate focus is macroeconomic.

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.

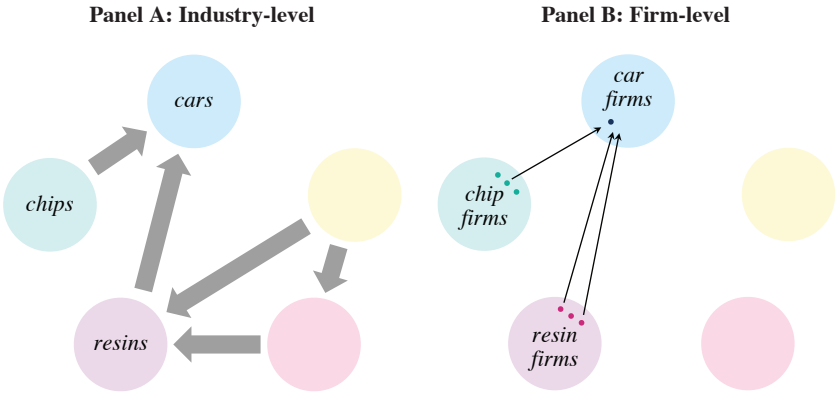
as we have defined them, they present some limitations. In this section, we interpret and critique the authors' discussion of dependencies.

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 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