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Networks and Economic Fragility

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Abstract

Many firms, banks, or other economic agents embedded in a network of codependencies may experience a contemporaneous, sharp drop in functionality or productivity following a shock—even if that shock is localized or moderate in magnitude. We offer an extended review of motivating evidence that such fragility is a live concern in supply networks and in financial systems. We then discuss network models of fragility, focusing on the forces that make aggregate functionality especially sensitive to the economic environment. The key structural features of networks that determine their fragility are reviewed, with an emphasis on the importance of phase transitions. We then turn to endogenous decisions, both by market participants (e.g., firms investing in network formation and robustness) and by planners (e.g., authorities undertaking macroprudential regulation). Fragility has some distinctive implications for such decisions.

1. INTRODUCTION

A fragile system is one that is vulnerable to a dramatic collapse. This can manifest in a variety of ways. For example, a local shock might precipitate a cascade of failures and have a global impact, or a small but widespread shock might bring a system to its knees. Complex systems are at risk of being fragile in these ways because they require many parts to work well simultaneously, so disruptions to individual parts have broader implications. In an example whose economic implications were famously drawn out by Kremer (1993), the Space Shuttle *Challenger* exploded because some simple rubber seals became too brittle in the cold. Economic systems can be analogously fragile. During the 2008 economic crisis, the real US economy seemed very sensitive to the good operation of financial markets for short-term debt, which were in turn destabilized by trouble in the market for subprime mortgages—a small part of the economy in many senses. During the worldwide pandemic of coronavirus disease 2019 (COVID-19), there have been simultaneous, severe shortages in many consumer goods as well as industrial goods and services, with effects rippling through many supply chains. Here, though the forces operating are less well understood, there is an obvious question about the role complex supply networks play in propagating shocks (Meier & Pinto 2020, Flexport Ed. Team 2021, Helper & Soltas 2021).

Complex systems are often thought of as networks of interacting, interdependent parts, and this perspective is especially helpful for understanding their fragility. For instance, in analyzing the 2008 financial crisis, we can trace a sequence of "dominoes" ranging from the failure of individual firms in the mortgage industry due to defaults by borrowers to the liquidation of major hedge funds invested in those firms. These events precipitated a stock market collapse and, finally, the termination of many unrelated real investment projects throughout the economy. Similarly, during the COVID-19 pandemic, consumers shifted their demand from services to goods, stressing shipping and logistics services. The resulting congestion at ports caused cascading delays and shortages even in goods not affected by demand shocks. At the same time, pandemic-related and other disruptions caused additional supply shocks. Only one of the many consequences of supply shortages was that the production of various auto parts was impaired, ultimately halting several carmakers' production lines. Whatever the fundamental source of shocks, the structure of supply networks shapes how they affect market equilibria. Network representations offer a natural formalism for analyzing these issues.

This review focuses on an emerging area of economic theory that uses models of networks to deepen our understanding of fragility and robustness in complex economic systems. Research in this area often abstracts from much of the detail of specific contexts, modeling relationships of complementarity and substitutability between the components in simple ways. The review focuses on the forces that amplify disruptions from a small to a systemic scale. Key roles are played by ideas from graph theory, such as bottlenecks, network flows, centrality statistics, cohesiveness, modularity—and, in random graph theory, percolation and phase transitions. The basic positive questions include: How does fragility change as individual nodes become dependent on others in a more complex way, requiring more things to go right? To what extent is fragility mitigated by investments of various kinds of redundancy being built into the supply network?

An important theme is that network phenomena introduce interesting features into the aggregate production function—the mechanics of when nodes can operate. They make outcomes (e.g., output) potentially very sensitive to parameters (e.g., the probabilities governing idiosyncratic risks). This is the essence of fragility, which, in turn, has major consequences for policy: A policy maker may be worried about catastrophic contagions and may design regulations in view of that. Similarly, banks and firms are often incentivized to take actions that reduce the likelihood of disruption to their own operations. Network forces and phenomena bear on these decisions. How do endogenous decisions about linking (e.g., whom to trade with) and robustness (e.g., how much to invest in the operations department) shape fragility? How and why do equilibrium outcomes differ from efficient outcomes that a planner might prescribe?

Network fragility is related to topics on which there are extensive literatures, in finance, macroeconomics, and operations, among other fields. We do not offer proper overviews of these literatures because there are excellent recent surveys that provide a more comprehensive overview than we can give (for surveys of research on the contagion of financial distress, see Allen & Babus 2009, Glasserman & Young 2016, Benoit et al. 2017, Jackson & Pernoud 2021; for surveys of research on macroeconomic volatility and sectoral interdependencies, see Baqaee & Farhi 2019, 2020; Carvalho & Tahbaz-Salehi 2019; and for discussions of operations research on supply network volatility, see, e.g., Wang & Disney 2016). Instead, we focus on research in each area that is closest to this review's main concerns: the theoretical supply-side forces shaping the reliability of a network. We are especially interested in shocks that (temporarily) disrupt production for some firms, how these interact with the network structure of interdependence, and how to identify fragilities in the system. Although the need for an economic theory of fragility in networked systems is becoming widely recognized, the development of such a theory is still at a formative stage, and this article reflects that.

We begin in Section 2 by presenting some evidence of fragility in supply networks and financial networks. The facts both highlight the importance of fragility broadly and suggest some specific questions that are not well understood even in very simple models of production. Then, in Section 3, we consider a toy model of a small supply network that is nevertheless rich enough to illustrate some of the key issues and network features relevant to robustness and fragility. In Section 4, we show how a large-network approach can be used to capture complexity. We illustrate the crucial role that phase transitions play in determining the fragility of a complex system; both continuous and discontinuous phase transitions emerge in different situations with different implications. Up to this point, the models we study are focused on the extensive margin of which firms can produce, and the distinctive network phenomena that operate on that margin. In Section 5, we discuss how such models can serve as a base for richer models of the supply side—for example, models featuring technological substitution. We consider endogenous actions that affect robustness in Section 6. In Section 7, we conclude by discussing some avenues for further research, both theoretical and empirical.

2. MOTIVATING EVIDENCE

We begin by presenting several real-world examples of cascading disruptions and the economic decisions that underlie them. The examples come from two domains: (*a*) supply networks in the real economy and (*b*) networks of financial dependencies.

Our coverage of these examples is not equal in depth. We devote more attention to supply networks because, especially in the context of the worldwide supply disruptions of 2020–2022, there are fewer existing reviews of the facts. On financial contagion, we can be briefer by drawing on prior research organizing key facts, as well as using analogies with supply network phenomena already covered. The goal of this section is to bring out those features in each domain that call for models focusing on network connections and discrete failures.

2.1. Supply Chain Disruptions

We begin with supply networks, first providing some illustrative anecdotes and then turning to more systematic evidence.

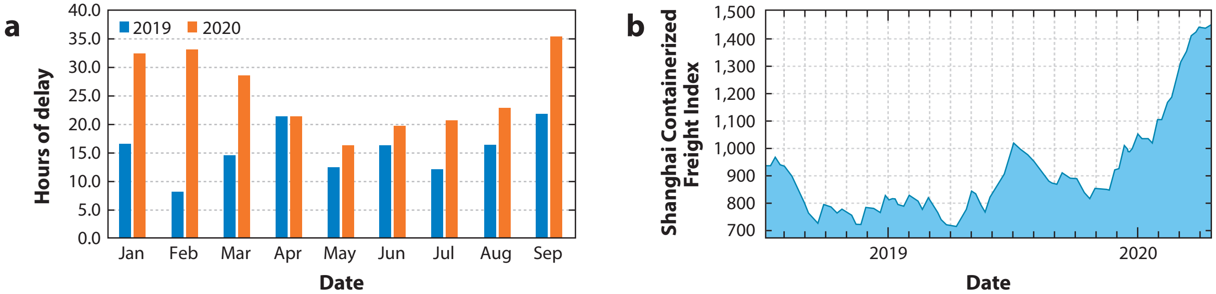

Figure 1

(*a*) The average number of hours of delay for ocean shipments by month in 2019 and 2020. (*b*) Changes in the Shanghai Containerized Freight Index, a weighted average of the price of shipping a container from Shanghai over 15 export routes, during the COVID-19 pandemic. Panels *a* and *b* adapted with permission from Beaulieu (2021).

2.1.1. Case studies. During the COVID-19 pandemic, much has been written about shortages of goods. From personal protective equipment to toilet paper, and from semiconductors to bicycle chains, supply chain problems have become a regular front-page issue in news coverage in both the business and general press. The White House Council of Economic Advisers circulated a report citing supply chain disruptions as a major event throughout the US economy and a contributor to inflation (Helper & Soltas 2021).

Several sources allow us to get a more quantitative sense of the severity of supply chain problems. On the basis of an analysis of 1.7 billion news feeds, Resilinc, a provider of supply chain resilience and risk management intelligence and analytics, identified 6,192 potential disruptions in 2020, an increase of 67% from 2019. Shipments have also been severely and systematically disrupted in recent times. Delays have increased for internationally sourced parts (**Figure 1*a***), while the cost of shipping (**Figure 1*b***) has simultaneously increased substantially.

Supplemental Material >

A striking commonality across many salient supply chain disruptions is that they ripple far beyond the locales and industries where they start.[1] For example, as we discuss in detail in **Supplemental Appendix A**, the 2021 shortage of computer chips caused problems for many automobile producers because several parts they need require computer chips directly or indirectly. Many other industries were also affected. The shortage is most severe for fairly basic chips that do mundane tasks like regulate power. Such components are present in a great many consumer products but represent only a tiny fraction of production costs. Nevertheless, sourcing these basic chips is essential, and the shortage has caused widespread disruption.

Another important feature of the computer chip shortage is that the industry is concentrated and there are few main suppliers. This means that disruptions to individual firms, such as Taiwan Semiconductor Manufacturing Company, can reduce the global production capacity for computer chips below the level demanded. Many similar examples exist. The 2011 Thailand flood halted production by Western Digital, a hard disk producer with a large market share, severely impacting global production of computers and in turn causing processor maker Intel to reduce its revenue forecast. As a result, Intel's stock fell by more than 4% on the same day (Nikolsko-Rzhevskyya et al. 2020). A 2012 fire at a German chemical plant responsible for approximately a quarter of the world's supply of cyclododecatriene—a precursor chemical to a resin widely used by automotive

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[1] There is also some evidence that the proportion of disruptions that can be attributed to direct suppliers fell during the first half of the 2010s, while correspondingly the proportion that could be attributed to companies further upstream increased (*Economist* 2021).

suppliers—halted several automakers' production lines. Similar consequences followed a February 2021 snowstorm in Texas, which also disrupted critical resin production and caused automobile manufacturers in the USA to halt their production lines (**Supplemental Appendix A** includes further details and examples).

Supplemental Material >

The cases just discussed show that disruptions to specific firms can cascade through the supply network and cause widespread problems. Regional disruptions, such as natural disasters, can have a similar impact in industries that are not as concentrated. This is because it is common for many firms in a given industry to colocate. Colocation was an important feature of the supply chain disruptions caused by the Great East Japan Earthquake. As discussed in **Supplemental Appendix A**, it caused Toyota, among others, to experience severe problems.

In response to the Great East Japan Earthquake, Toyota has made efforts to map out its supply network. So far, this mapping has reached 10 levels deep and identified 400,000 items that Toyota sources directly or indirectly (McLain 2021). Choi et al. (2021) report that when a global semiconductor giant tried to map its vulnerabilities to vendors three and four levels upstream, it took a team of 100 executives more than a year to determine the firms in its extended supply network. Although Toyota's efforts to better understand its supply network and address vulnerabilities were costly, they appear to have helped it during the COVID-19 pandemic (see **Supplemental Appendix A**).

This evidence suggests that supply networks are deep, meaning that there are many layers of specific, disruption-prone sourcing. The number of items and firms involved in these surveys, even at only a few levels deep, also makes clear that dependencies "fan out" quickly: Each supplier relies on many customized inputs (rather than production having a linear, assembly-line structure). Thus, the networks also have high breadth.

2.1.2. Broader evidence: the importance of relationships.

So far, our discussion has been based on anecdotal evidence and examples, but a more systematic analysis leads to similar conclusions. Carvalho et al. (2020) track the disruptions associated with the Great East Japan Earthquake throughout the production network and find a significant decrease in sales for firms with direct suppliers in disaster areas. Moreover, these problems propagated further downstream to the disaster area firms' indirect customers and upstream to the suppliers of firms hit by the earthquake. Similarly, Barrot & Sauvagnat (2016) investigate the consequences of firm-specific shocks and find evidence of propagation and fragility. Using data on natural disasters, they focus on local propagation patterns from a firm to its immediate customers. Shocks to suppliers drop the sales of their customers; the effect is especially strong when the disrupted supplier is producing hard-to-substitute relationship-specific inputs. Customization thus plays an important role in the propagation mechanism. Moreover, in such cases, the shock further propagates to other (unaffected) suppliers of the customer firm. The effects of the shocks are substantial, although their impact is temporary and observed only when the relationship between customers and suppliers is active.

Other recent empirical evidence further supports shock propagation through supply networks. Foerster et al. (2011) show that what could appear to an econometrician as common shocks may instead be the result of endogenous comovement generated by the equilibrium interactions between various industries in a production network. The authors use a structural estimation to find that industry-specific shocks amplified in this way can account for a nontrivial share of macroeconomic volatility.[2] Relatedly, Horvath (2000) and Carvalho (2010) calibrate a multisector model

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[2] Their structural model relies on Cobb–Douglas technology, but Atalay (2017) extends their result to a model with a constant elasticity of substitution technology and find that industry-specific shocks are even more important.

(under the assumption of uncorrelated disturbances to quantify the macroeconomic importance of idiosyncratic shocks). They find that idiosyncratic shocks, amplified by interactions, can account for approximately two-thirds of aggregate fluctuations.[3],[4]

Supplemental Material >

2.1.3. Summing up.

Several insights related to the structure of supply networks and fragility can be drawn from this discussion (and are further supported by **Supplemental Appendix A**):

- Inputs are often sourced from specific suppliers and customized, rather than bought off the shelf. The corresponding supply networks can be very complex, both broad and deep.
- The network of interdependencies among firms can propagate shocks far beyond the products and locales where they originate and cause disruptions elsewhere. This problem is acute when multiple suppliers of the same good rely on a shocked firm further upstream in a supply network. Colocation of firms within an industry can create similar problems when it makes several of them vulnerable to the same shock.
- Disruptions are relatively frequent and have become more frequent during the COVID-19 pandemic.
- Firms can make costly investments to better withstand shocks and make their supply networks more robust.

These observations raise some important questions. In general, how does the network structure matter for individual nodes' robustness, and when does individual fragility translate into systemic fragility? To what extent do firms have incentives to make efficient investments in the robustness of their supply networks? Actions such as holding larger inventories, multisourcing (i.e., using multiple alternative suppliers to source a given input), and fostering strong supply relationships can mitigate problems, while firms' efforts toward understanding of weak points in their supply networks can help them anticipate and prepare for problems. What do robust networks look like, and what are the wedges between individual incentives and social welfare?

In addition to these theoretical questions, obvious empirical issues are raised by the discussion. These call for improved measurement and empirical modeling of what entire supply networks look like in practice and how fragile they are. We defer discussion of these questions to the conclusion (Section 7), after we have established the terms and concepts needed to ask them precisely.

2.2. Financial Contagion

Many of the phenomena mentioned in our discussion of supply networks also have manifestations when we consider the potential fragility of financial systems. Financial institutions often rely on relationships with one another,[5] and the financial interdependencies created by trade between them is complex. Such interdependencies involve many types of contracts across many asset types, including short-term borrowing and lending, reinsurance, and proprietary trading positions across a range of derivative products. A common thread, however, is that such relationships make financial institutions dependent on one another. Financial products rely on many other contracts to

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[3] Grassi (2017) allows for oligopolistic competition between firms (see also di Giovanni et al. 2014, Kikkawa et al. 2018). Acemoglu et al. (2016) study how shocks propagate across industries and find evidence in support of shocks propagating downstream.

[4] An alternative channel through which idiosyncratic shocks might matter has to do with firm size. Gabaix (2011) shows that the idiosyncratic movements of the largest 100 firms in the USA appear to explain approximately one-third of variation in output and the Solow residual.

[5] For example, Hendershott et al. (2020) show that insurers and dealers maintain a limited number of relationships with one another in the over-the-counter corporate bond market.

function as expected. The failure of a financial institution to fulfill some of its obligations (e.g., loan payments) leads to losses, including asset liquidation costs that can be exacerbated by fire sales, legal fees, and other disruptions. Thus, following a failure of an institution, the value of its counterparties will decline, creating the possibility of cascading failures. This systemic risk means that a financial institution can be affected by events in the financial network not local to it. (For detailed postmortems of the 2008 financial crisis, see FCIC 2011, Bernanke 2018.) Ultimately, such distress can have ramifications for the real economy, leaving assets idle or inefficiently allocated.

The chance of localized shocks leading to cascading failures and becoming important at an aggregate level depends on the overall structure of the financial network, analogously to the situation in production networks. Indeed, in supply networks, disruption of key firms or industries can cause widespread problems; in financial networks, systemically important financial institutions play an analogous role. In the case of financial networks, empowered by legislation such as the Dodd–Frank Act, regulators have sought to identify systemically important financial institutions and subject them to tighter financial regulations. These policies are directly motivated by protecting the robustness of a financial system.

Turning from contagions to correlated shocks, there is a financial network counterpart of the supply network phenomenon of the colocation of firms in a given industry—financial institutions exposed to the same fundamental assets. Many retail banks were simultaneously exposed to defaults in subprime mortgages during the 2008 financial crisis, which contributed to the probability of both individual and joint failure. When banks that are strong trading partners with one another hold similar asset positions external to the financial system (e.g., they lend to the same industries or types of households),[6] this can be particularly problematic.

While some of the dangers of interconnectedness are similar across supply networks and financial networks, some systemic risk phenomena are distinctive to the financial setting. For example, there is now wide-ranging evidence that, across a number of financial markets, trading relationships are arranged in a core–periphery structure (e.g., Boss et al. 2004, Iori et al. 2008, Craig & von Peter 2014, Fricke & Lux 2014, in ’t Veld & van Lelyveld 2014, Langfield et al. 2014). Large financial institutions occupy the core positions and have strong interdependencies with one another; they then link to smaller (often regional) periphery financial organizations that have no direct links to one another.

Nevertheless, many of the important questions regarding financial network fragility closely mirror those for supply networks: How does the network structure affect individual robustness? When does individual node–level fragility translate into aggregate fragility? What externalities may cause financial networks to be configured in a way prone to too much fragility, and how can policies aid in the creation of more robust financial systems?

3. SOURCES OF FRAGILITY: A SIMPLE MODEL AND KEY FORCES

This section introduces a basic model of network interdependence with discrete failures at the firm level. It allows us to capture certain key features of a production network important for the phenomena introduced in Section 2. The key features of the model are that there are multiple stages of production and that each stage may require the combination of complementary inputs.

We begin with an illustrative toy version of the model. Despite being parsimonious, it is rich enough to discuss several key forces. These include the effects of multisourcing, concentrated

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[6] For example, Elliott et al. (2021a) provide evidence that German banks that have stronger financial ties with one another have more correlated real exposures.

indirect dependence on common upstream suppliers, and the correlation structure of shocks. After presenting these ideas in simple, small examples, we build up to richer models.

The basic model generalizes Kremer's (1993) O-ring model, a canonical analysis of the reliability of a many-step production process. The modeling of complementarities and multisourcing is an adaptation of research by Elliott et al. (2022), while the modeling of concentrated indirect dependence is based on research by Bimpikis et al. (2019). The issues modeled also clearly relate to the concerns of the literature in macroeconomics on production networks; however, our main concern here is the extensive margin of which nodes can produce in the short run following shocks. To focus on this issue, we initially abstract away from some general equilibrium considerations. Section 5 connects our perspective here with the frontier of modeling in macroeconomic and financial networks, while Section 6 discusses endogenizing the network structure.

3.1. A Basic Network Model of Production

There are three products in the economy: a final product a, an intermediate product b required to produce a, and an intermediate product c required to produce b. Both inputs are customized and must be sourced via specific supply relationships; neither product b nor product c can be purchased off the shelf. For now, we focus on a single firm producing the final product a; this firm is labeled $a1$. Suppose there are two potential suppliers of product b, labeled $b1$ and $b2$; and four potential suppliers of product c, labeled $c1$ through $c4$.

Not all potential suppliers can supply a given firm. There is a network among the firms representing which can supply which. Each firm has links directed from itself to those firms from which it can source, and there are no constraints on how much can be supplied along any such link.[7] In practice, there are many reasons why not all possible suppliers of an input are able to trade with all producers requiring that input. Firms may need to have specific knowledge about the requirements and capabilities of their trading partners; they may need an ongoing relationship to overcome moral hazard problems; there may be geographical restrictions on trade when transportation costs are high. (For more discussion and modeling of such phenomena, see Board 2011, Lippert & Spagnolo 2011, Andrews & Barron 2016; for an ethnographic study documenting the extensive use of supply relationships and the benefits they provide, see Uzzi 1997; and for a broader bibliography of the evidence on this point, see Elliott et al. 2022.) Whatever the reason, there is ample evidence that disruptions to a firm propagate in the supply network (see Section 2), and that firms are often unable to source alternative products in the short term—at least on timescales of a business quarter or less (Barrot & Sauvagnat 2016).

Suppose firm $a1$ sources (only) from $b1$, which sources (only) from $c1$. **Figure 2*a*** represents an example of such a supply network for firm $a1$.

We now introduce shocks. Each firm may be hit by a shock that prevents it from producing, for one reason or another. Continuing with the example in **Figure 2*a***, suppose that $a1$, $b1$, and $c1$ are each hit by a shock, independently, with probability $1 - x$; with probability x, each is unshocked. The variable x is called the firm's strength; it measures how resistant a firm is to idiosyncratic shocks.[8] We call a firm functional if it is able to produce. The most upstream firms are functional if they are unshocked, while other firms are functional if they are unshocked and able to source all their required inputs from functional firms.

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[7] We introduce capacity constraints and consider richer substitutability possibilities in Section 5.

[8] For simplicity, we illustrate our examples mostly with homogeneous strengths across the network, though it will be clear how to generalize many of the calculations.

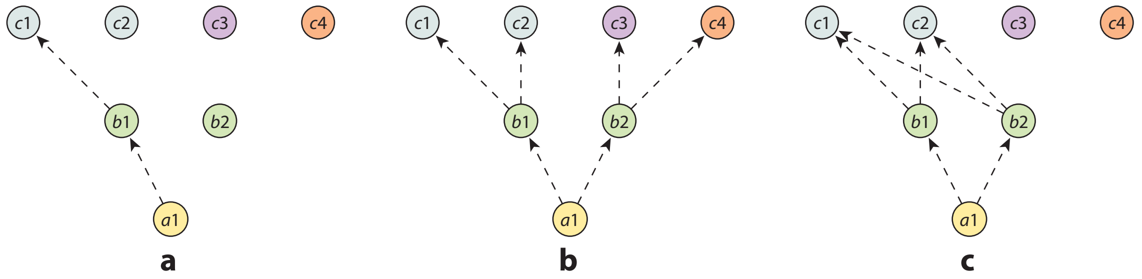

Figure 2

(*a*) A possible supply network for firm *a*1, depicting all firms upstream of it. Higher nodes are more upstream. An arrow indicates that, for example, *a*1 can source from *b*1. Colors represent the regions in which firms are located. (*b*) Multisourcing: *a*1 can source from either *b*1 or *b*2, while both *b*1 and *b*2 have two alternate suppliers for their *c* input. (*c*) Multisourcing: *b*1 and *b*2 depend on the same suppliers.

The firm's reliability is defined as the probability that it is functional. In our first example, firm *a*1 is functional with a probability equal[9] to x^3.

We can see that, even when each firm is unlikely to be shocked (i.e., when x is close to 1), there is a substantial risk, equal to $1 - x^3$, that *a*1 is not functional. For example, if $x = 0.9$, (so that the shock probability is 0.1), then the reliability of *a*1 is slightly less than 0.73. Moreover, as the final product gets more complex, requiring a deeper supply network with more levels of indirect sourcing, this risk increases. With k levels, the probability that the supply network is functional is x^k. We call this scenario Case I, and we compare *a*1's reliability in this case with various other supply network configurations and shock distributions as we proceed.

An alternative interpretation of this simple model of sourcing is that there is only one level, which means that there are no suppliers upstream of firm *i*'s suppliers[10] but that multiple essential inputs are directly required by firm *i*. Inputs are called essential if the failure to source any one of them prevents production. In this case, too, the probability of successful production is x^k when k inputs are required.

The significant potential implications of these strong complementarities—both within a single firm's production and across the economy more broadly—were emphasized in an influential paper by Kremer (1993), who showed that strong complementarities could provide a unified explanation for several empirical relationships. For example, the fact that rich countries can achieve a higher x implies huge productivity differences across countries for processes that are at all complex, because even for a moderate k, differences in x can be amplified a great deal in the function x^k. Poor countries (or firms) that cannot achieve a high x will tend to focus on simpler (lower k) production, while richer ones will invest heavily in making x high across all inputs.

Since Kremer's (1993) paper, a number of works have examined such complementarities further and found them helpful in explaining a variety of phenomena (e.g., Ciccone 2002, Acemoglu et al. 2007, Levchenko 2007, Jones 2011, Levine 2012). These studies have delved more deeply into complementarity-based explanations for (*a*) very large cross-country differences in production technology and aggregate productivity, (*b*) rapid output increases during periods of industrialization, and (*c*) the structure of production networks and patterns in international trade flows. Most importantly for our concerns, strong complementarities provide a significant amplification

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[9] Firm *a*1 is functional if *a*1, *b*1, and *c*1 are all unshocked, which, because shocks are independent, occurs with probability x^3.

[10] Practically speaking, this means that *i*'s suppliers do not need to source from anyone at risk of failure; they may rely on inputs, but ones that can be bought off the shelf.

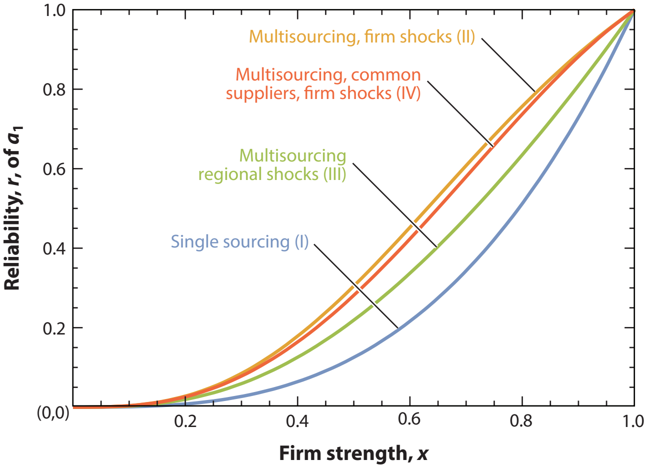

Figure 3

Firm *a*1's reliability is plotted as firm strength *x* varies under Cases I through IV.

mechanism for shocks, helping to explain the sensitivity of aggregate outcomes to microeconomic shocks (Jones 2011, Baqaee & Farhi 2019).

3.2. Multisourcing

As discussed in Section 2, firms can take actions that increase their reliabilities. One important way to combat the production risk caused by strong complementarities is via multisourcing (Sheffi & Rice 2005). In this subsection, we introduce multisourcing—the common practice of having several alternative suppliers for the same input—into our model and show how it can dramatically improve reliability. We then turn to phenomena that can degrade reliability even in the presence of extensive multisourcing.

3.2.1. The basic multisourcing model and the case of firm-specific shocks.

We begin by introducing multisourcing into our model. Suppose that each firm maintains relationships with two potential suppliers (**Figure 2*b***). Firm *a*1 now sources from both *b*1 and *b*2, while each of these firms also sources from two other firms. As above, suppose that each firm is hit by an independent shock with probability $1 - x$. We call the combination of multisourcing and independent shocks Case II. Recalling that, for now, we assume each link has unlimited capacity, we can work out each firm's reliability.[11] **Figure 3** plots the reliability of *a*1 as a function of (homogeneous) firm strength *x* for several cases, including Case I (the single-sourcing line discussed above) and Case II, which we have just described.

Indeed, the lowest-reliability curve in this figure is that of Case I, while the highest is that of Case II. Single sourcing (arranged in a single-file pattern) is the least reliable (for any strength), while multisourcing with independent shocks is the most reliable. Multisourcing substantially increases the reliability of *a*1, particularly for intermediate firm strengths. For example, when firm strength is 70%, multisourcing increases the probability that *a*1 is functional from 34% in

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[11] The probability that each *c* producer is functional is x. Each *b* firm is functional if at least one of its *c* producers is functional and the firm itself is unshocked: $x[1 - (1 - x)^2]$. Finally, by similar reasoning, we find that the probability that *a*1 is functional is $x(1 - (1 - x[1 - (1 - x)^2])^2)$.

Table 1 Case labels for the different scenarios considered[a]

	Single sourcing	Multisourcing	Multisourcing common suppliers
Firm-specific shocks	I	II	IV
Regional shocks	I	III	I

[a] Because $a1$'s reliability is the same under single sourcing (both shock structures) and multisourcing with common suppliers and regional shocks, these scenarios are all assigned the Case I label.

Case I to 61% in Case II, an increase of almost 80%. For deeper supply networks, the contrast would be even more dramatic.

So far we have considered single sourcing and multisourcing with firm-specific shocks. In the next two subsections, we introduce regional shocks and the possibility of dependence on common indirect suppliers and discuss the remaining combinations shown in **Table 1**.

3.2.2. Correlated shocks.

As mentioned in Section 2, suppliers of a given intermediate good often cluster together geographically. Firms clustering in this manner can realize agglomeration externalities, thereby increasing their productivity and profits. But, as discussed in Section 2, such colocation can cause suppliers to fail simultaneously. Our simple model can help analyze how colocation can undermine the benefits of multisourcing for supply network robustness. More generally, the improvement in robustness facilitated by multisourcing will depend on the shock structure.

Incentives to colocate are present for both vertically related and horizontally related firms. So, even if a producer of a given intermediate good were to locate away from its competitors, it might have to source its inputs from its own region (Linton & Vakil 2021).

To incorporate colocation into our running example, suppose that some suppliers operate in the same region and that shocks are regional—that is, all firms located in the same region are hit by a shock to that region. Specifically, we assume there are five regions that are hit by shocks independently with probability $1 - x$. Firms $c1$ and $c2$ are located in region 1; firms $c3$ and $c4$ are in regions 2 and 3, respectively; firms $b1$ and $b2$ are in region 4; and firm $a1$ is in region 5. We call this situation Case III. Given this shock structure, multisourcing is less effective at increasing the reliability of $a1$ (**Figure 2*b***). The probability that $a1$ can function is now $x^2[1 - (1 - x)^3]$. To calculate this probability, we first note that $a1$ can function only if both regions 4 and 5 are unshocked. This occurs with probability x^2. It must also be the case that at least one c producer is functional, which occurs when at least one of regions 1, 2, and 3 is unshocked; the probability of this is $1 - (1 - x)^3$. **Figure 3** includes a plot of how the reliability of $a1$ varies with x for Case III.

3.2.3. Common suppliers and concentrated indirect dependence.

Beyond the possibility of common shocks, there is a distinct mechanism for perhaps unexpected fragility despite extensive multisourcing. Even when there are multiple suppliers to a given firm, these suppliers may rely on the same firms upstream and may hence be vulnerable to the same shocks (as discussed in Section 2). Indeed, one of the points emphasized by Bimpikis et al. (2018) is that individual firms' reliabilities are insufficient for evaluating global robustness. Instead, the joint probability distribution needs to be considered. Even for the functionality of a single firm, what matters is the event that all of a firm's suppliers of a given input are simultaneously unable to supply it. Common indirect upstream suppliers make such an event more likely and undermine supply network robustness. In effect, common indirect suppliers create correlation in the functionality of a firm's suppliers—not through the shock structure but through the network dependencies themselves.

To incorporate both common indirect suppliers and regional shocks into our running example, suppose that all firms are multisourcing but that the two producers of b use the same two producers of c (**Figure 2*c***) and that shocks are again regional, with the groupings described above. The probability that firm $a1$ is functional is then $1 - x^3$. This is the same probability as for Case I, with single sourcing (**Figure 2*a***). In stark contrast to the limited harm of common suppliers alone that is seen in Case IV, the combination of regional shocks hitting some suppliers at the same time and indirect dependence on the same suppliers upstream renders multisourcing completely ineffective.

So far, we have shown how shocks can propagate and hence be amplified by the interdependence of firms in supply networks. We have done so in a very simple model with only three layers of production and each firm needing to source only one type of input to produce. In reality, as described in Section 2.1.1, supply networks can be much more complex in terms of both depth and breadth. In the next section, we examine the reliability curves of the type shown in **Figure 3** in larger networks.

4. LARGE NETWORKS AND PHASE TRANSITIONS

The analyses presented in the previous section are local, concerning phenomena that manifest with only two or three layers of production. As networks become larger and more complex, our main object of study remains the same: the reliability of a network as a function of exogenous parameters, especially firm strength. But new questions arise. When is production possible in a network with many stages? How do breadth (more complementarity at each stage) and depth (more stages of production) differ? How does the reliability of production degrade as individual firms grow weaker? We focus on varying the strengths of firms. Analytical methods of branching processes and random graph theory turn out to yield a rich analysis of such questions and uncover new phenomena in the large network setting.

Perhaps the most striking phenomena that occur in large networks are phase transitions. Such transitions are associated with fundamental changes in qualitative behavior, as when ice melts into water. In our context, the qualitative properties that we study concern the shape of the reliability curve.

We organize this section around two different types of phase transitions, discussing continuous ones first, followed by discontinuous ones. This distinction is important, and both types of phase transitions arise in different applications. We continue to focus on production/supply networks and financial networks, drawing on the modeling framework of Elliott et al. (2022) as an organizing thread. The complexity of a contagion process, in a suitable sense, turns out to be key to fragility in production networks. The final subsection highlights some other economic models of complex contagion and the distinct kinds of fragility that have been examined there.

4.1. Continuous Phase Transitions

We begin by demonstrating a continuous phase transition in the basic model of production we have been working with. We then show that it is a manifestation of a canonical type of phase transition known in various random graph models, for instance, of disease spread or connectivity.

4.1.1. Simple production. Consider the basic structure shown in **Figure 2*b***, but with greater depth. Each stage involves sourcing one disruption-prone input.[12] As above, we focus on the firm that is most downstream. Firms that are ℓ steps downstream of the most upstream level are said to

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[12] As a matter of interpretation, there may be more than one physical input at each stage. The key assumption is that all but one are sourced as commodities rather than through specific supply relationships, so only one input is subject to disruption via shocks to these firms.

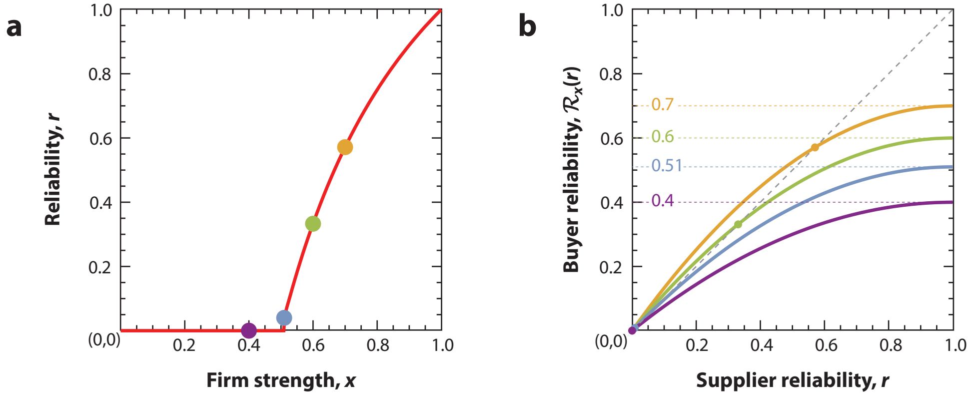

Figure 4

(*a*) The probability of successful production of a simple good as relationship strength varies, with $n = 2$ potential suppliers at each stage. (*b*) The reliability $\mathcal{R}_x(r)$ of a focal firm as a function of r, for various values of x. The marked intersections with the 45° line reflect limit reliabilities. The marked points correspond to their counterparts at the same height.

be level ℓ.[13] At each stage, each firm has n perfectly substitutable sourcing possibilities for the one customized input that it needs. We focus on the case of firm shocks: Each node is independently hit by an exogenous shock with probability $1 - x$.

We study the reliability of the most downstream node, which we think of as the final good producer, for a network where this producer's level ℓ is large.[14] This gives us the simplest manifestation of phase transition behavior as the probability of idiosyncratic firm-specific shocks increases. When firm strength is sufficiently high, reliability has a strictly increasing, concave dependence on it. In contrast, when firm strength is below a critical level, production of the final good is not possible and therefore insensitive to strength. **Figure 4*a*** illustrates this pattern, with reliability (in the high-ℓ limit) having a kink at $x = 0.5$.

To explain the qualitative transition, we present a simple calculus for computing reliabilities for any level. Consider the event that a firm at an arbitrary level ℓ can produce. In the trivial case where the firm is at level 0 and has no specific supply relationships (i.e., needs to source only standard off-the-shelf inputs), we stipulate that $\rho(x, 0) = x$: The firm operates only if it is not exogenously shocked. For a firm at level $\ell \geq 1$, it is functional if it is unshocked (probability x) and at least one of its direct suppliers (at level $\ell - 1$) is functional. Because each of these is independently functional with probability $\rho(x, \ell - 1)$, this gives rise to the following equation:

$$\rho(x, \ell) = x\big(1 - [1 - \rho(x, \ell - 1)]^n\big). \qquad 1.$$

We inspect this type of equation and its mechanics in a more general version of the model in the next subsection, but for now we can derive one intuitive consequence. It is apparent that $\rho(x, \ell)$ is decreasing in ℓ, so it converges as $\ell \to \infty$ to some number $r = \rho(x)$. We can think of this number as $\rho(x, \infty)$, the reliability of both a firm and its suppliers when ℓ is high. When the reliability of a

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[13] The supply chain literature sometimes uses the terminology of tiers: tier 1 for direct suppliers, more upstream ones at tier 2, and so forth. Our levels are numbered in the opposite way, which is more convenient for our calculations.

[14] The phenomena we discuss are evident, though of course only approximate, for moderate values of ℓ such as 7 (i.e., for realistic depths in view of the motivating evidence in Section 2).

firm is the same as that of its suppliers, Equation 1 simplifies to

$$r = \underbrace{x[1-(1-r)^n]}_{\mathcal{R}_x(r)}. \qquad 2.$$

The limit reliability $\rho(x)$ is in fact the largest solution of this equation. As a result, we can plot ρ as a function of x, as we do in **Figure 4**. For any fixed value of x, we simply look at the largest value of r at which the curve on the right-hand side of Equation 1, $\mathcal{R}_x(r)$, intersects with the 45° line (**Figure 4*b***). Note that when x is sufficiently low, the only intersection is at zero; then, as x increases, a higher intersection (near zero) emerges. The sudden emergence of this nonzero intersection corresponds to the kink in $\rho(x)$ in **Figure 4*a***.

The kink in the probability of successful production around the threshold of 0.5 is a continuous or first-order phase transition: At a certain critical point, the dependence of ρ on x qualitatively changes. This kink is related to the emergence of a giant component in an Erdös–Rényi random graph—indeed, it is really a version of the same phenomenon. The transition has obvious economic implications. From a planner's perspective, increasing the strength of all nodes has zero marginal value for x below 0.5, and suddenly quite a large marginal value for x just above 0.5.

4.1.2. First-order phase transitions: general principles.

We have focused in this section on a production network application, but the analysis of the first-order phase transition is a linchpin of network analysis. Equation 2, which characterizes limit reliability, also has many closely related manifestations and applications.

Consider a random network on a large number N of nodes. A given node has a random number of neighbors, governed by a degree distribution, and these neighbors are drawn at random from the rest of the population (see Jackson 2008, chapter 4, for details). Suppose each node is "disabled" with probability $1 - x$. (Alternatively, we could also disable the links in the network.)

We give two social/economic interpretations of this situation to aid intuition:

1. Consider an epidemic of a disease or information.[15] The nodes are individuals, who can be infected or not. A fraction $1 - x$ of the population is exogenously immune, while the rest are susceptible. Some node is initially infected. Any infected node infects all its susceptible neighbors. (Here, the random graph corresponds to interactions that pass the infection; this might be a random subset of all interactions.) We can then ask: How many people will be infected? More specifically, what proportion of the population should we expect to become infected as the population gets large?
2. Consider a trading network. Each node is a trader, which can be active or not. A fraction x of traders are exogenously active. The random graph represents exogenous connections that permit trade. A buyer and a seller are selected uniformly at random from the population. They can generate surplus only if there is a path in the network of active traders connecting them.[16] What is the probability that they can trade?

In each case, we can write a formula analogous to Equation 1 to compute the fraction of nodes that are connected, in a relevant sense, to a randomly selected node. For example, in case 1 we are interested in the fraction r of nodes that have a path of susceptible nodes leading from them to the random source of the infection, and that will therefore be infected. The formula in Equation 2

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[15] We use the language of infection, keeping in mind that it can be reinterpreted in the information context.

[16] For early antecedents taking a graph connectedness approach to contracting opportunities, see Bernheim & Bagwell (1986, 1988). More recently, trading network models have been studied by, for instance, Goyal & Vega-Redondo (2007), Choi et al. (2017), and Aymanns et al. (2020).

captures a fixed-point relationship that should be satisfied by r asymptotically as the network grows large. A node is linked to the source via susceptible nodes if and only if it is susceptible (not exogenously immune) and if at least one of its neighbors is susceptible and linked to the source via susceptible nodes. In a large network, the randomly drawn neighbors are effectively independent, so r satisfies a fixed-point condition analogous to Equation 2.[17] Very similar reasoning applies to case 2. In each case, there is a continuous, or first-order, phase transition similar to the one we have seen in the production model.

The examples we have given highlight a need for richer models of local interdependence. For example, when firms need to source multiple inputs, they are often more vulnerable than our simple model captures, because they exist in multilevel supply networks and require multiple types of links to work simultaneously (links to source various different inputs). Section 4.2 develops the analysis of reliability to cover this case.

4.1.3. Continuous phase transitions in a network of financial interdependencies.

We now reinterpret the model developed above as a very simple representation of financial contagion. Doing so allows us to demonstrate how continuous phase transitions can manifest in financial networks. In Section 5.3, we build on this model to obtain a richer representation of financial interactions.

Let each node in the network be a bank, which can be solvent or not. Suppose that, exogenously, a fraction $1 - x$ of the banks, selected uniformly at random, are safe—that is, they have strong balance sheets and are not prone to insolvency. The other banks are potentially vulnerable, and each becomes insolvent if a neighbor becomes insolvent. This model entails a very simplified approach to what happens on banks' balance sheets: Implicitly, it is assumed that insolvency involves sufficient reduction in value and that each bank depends enough on each counterparty.

A random graph represents financial interdependencies. Here we may take links to be directed, so that a link from i to j represents that i is dependent on j. Therefore, a bank remains solvent only if all of the banks it is dependent on are solvent. One bank is randomly shocked to become insolvent. We are interested in the size of the set of banks that are ultimately rendered insolvent by a contagion of insolvency from the shocked bank. This set consists of the banks that are connected in the financial network directly or indirectly to the shocked bank. As the density of the network increases, a phase transition occurs, and the system suddenly changes from one in which only a small (vanishing) fraction of banks ever fail to one in which a nonvanishing fraction of the banks fail on average as $n \to \infty$. This corresponds to a large number, though perhaps a small fraction, of banks. The example described here is a special case of a model studied by Blume et al. (2011).

In Section 5.3, we discuss models of financial interdependencies with room for much richer intensive margins (capturing the size of debts, for example) and correspondingly more complex rules for contagion. We show that the basic network connectivity forces we have introduced here remain relevant.

4.2. Complex Production and Discontinuities

We now consider how a different type of phase transition can arise. This type of phase transition features a discontinuity in the aggregate production function.

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[17] In the supply chain example, the analogous notion of independence held exactly, because the subtrees of a node's suppliers were completely independent. Here, there is the potential for links between them, but in a large enough network this dependence vanishes asymptotically, under suitable conditions on the degree distribution (for details and references, see Jackson 2008, chapter 4).

4.2.1. Complex production.

We now present a generalization of the model in Section 3.1 in which each node may require multiple types of inputs (rather than one type of input sourced from many potential sources). This richer model gives rise to a new kind of phase transition.

Each product now simultaneously requires $m \geq 2$ distinct input products. Each firm has relationships to obtain them, perhaps using multiple suppliers for a given input (the redundancy being familiar from Section 3.1). We focus on a symmetric example in which each firm has n potential suppliers of each input. As above, we abstract for now from capacity constraints and posit that a firm can produce as long as at least one of its input suppliers can produce—but now this condition must hold for each input. As in the previous examples, we study multilevel supply networks. Level-0 firms are the most upstream. Level-1 firms source from them and supply level-2 firms, and so on. Level-0 firms do not rely on any other firms (but are susceptible to shocks with probability x, like every other firm).

Let us calculate the probability that a given firm at level ℓ is functional and illustrate some new phenomena that arise. Denote the probability that a firm at level ℓ is functional when firm strength is x by $\rho(x, \ell)$. First, we have $\rho(x, 0) = x$ by definition, as firms at level 0 are sure to be functional as long as they are unshocked. Then, paralleling our analysis in the single-input case above, for a suitably defined function $\mathcal{R}_x : [0, 1] \to [0, 1]$, we can write the level-ℓ reliability in terms of the level-$(\ell - 1)$ reliability:

$$\rho(x, \ell) = \mathcal{R}_x[\rho(x; \ell - 1)]. \tag{3.}$$

Indeed, more explicitly, the function that makes this true is

$$\mathcal{R}_x(r) = x[1 - (1 - r)^n]^m. \tag{4.}$$

To see this, fix a firm and consider any one of its inputs. If any given supplier of that input is functional with probability r, the probability that at least one of them is functional is then $1-(1-r)^n$, so the probability that all required inputs can be sourced is $[1-(1-r)^n]^m$. Finally, even if the firm can source all its required inputs, it will not be functional if it is shocked itself. The probability the firm is not shocked is x, yielding Equation 4 (here we are assuming that all shocks are independent events).

By repeatedly applying Equation 3 starting with $\rho(x, 0) = x$, we obtain a decreasing sequence of reliabilities (**Figure 5*a***). We are interested in $\rho(x)$, the reliability $\rho(x, \ell)$ in the large-ℓ limit. This limit reliability is given by the largest solution of $\mathcal{R}_x(r) = r$. Intuitively, for deep supply networks,

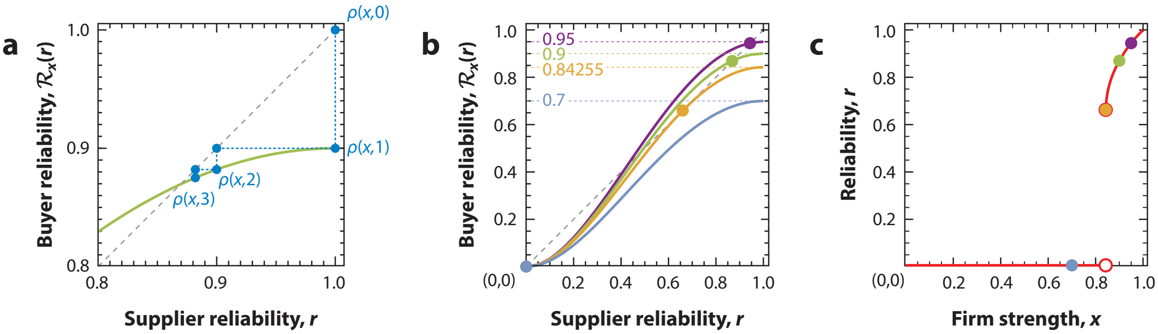

Figure 5

(*a*) The iterative computation of reliability using the 45° line. This computation uses the reliability curve $\mathcal{R}_x(r)$, which describes the dependence of a buyer's reliability on its suppliers' (symmetric) reliability. (*b*) Reliability for various x when $n = m = 2$. The values of x are shown as the heights of the curves at $r = 1$. (*c*) Reliability $\rho(x)$ for deep supply networks as firm strength x varies.

a producer's position in the supply network will be essentially equivalent to that of its suppliers, so its reliability should also be the same. By analyzing this fixed point, we can, as above, trace out how $\rho(x)$ depends on x.

Figure 5*c* shows the typical behavior of $\rho(x)$ for any complexity $m \geq 2$ and any multisourcing level $n \geq 2$, once depths become large (Elliott et al. 2022). **Figure 5*b*** illustrates the intuition for the sharp transition: A typical curve represents the probability that a given firm is functional as a function of the reliability, r, of its suppliers. The curve $\mathcal{R}_x(r)$ is shown for several values of x. The reliability levels r that are fixed points of $\mathcal{R}_x(r)$ in Equation 3 are given by its intersections with the 45° line, illustrated in **Figure 5*b*** for several values of x (each corresponding to one of the curves). As we vary firm strength x, such intersections give rise to the reliability curve plotted in **Figure 5*c***; the r corresponding to the largest intersection is the reliability associated with x.

For high enough x, the function $\mathcal{R}_x(r)$ has a fixed point with $r > 0$. When x is below a certain critical value, the graph of $\mathcal{R}_x$ has no nonzero intersection with the 45° line, implying that the reliability of high-ℓ suppliers (far downstream) converges to zero. Crucially, the largest fixed point of $\mathcal{R}_x(r)$ does not decrease continuously to zero as we lower x. Instead, it drops discontinuously when x decreases past x_{crit}—defined as the (strictly positive) value of x where there is a point of tangency between $\mathcal{R}_x(r)$ and the 45° line. Contrasting this case with simple production ($m = 1$), as shown in **Figure 4*b***, reveals the role that the convex-then-concave shape of the $\mathcal{R}_x$ curve plays for $m > 1$ in creating a precipice.

Comparing the cases of simple production, with one input required at each stage, and complex production, we see that aggregate output as a function of shock probability has very different shapes. In the simple case, there is a kink at a critical point, but the output curve is continuous. In the complex case, production collapses discontinuously at the critical value of x. As we have shown by comparing **Figures 4*b*** and **5*b***, the shape of the function $\mathcal{R}_x$ underlies this difference. We have focused on the manifestation of this kind of discontinuous phase transition in supply networks, one of our central applications. Related phenomena play an important role in other network-theoretic models, and we now review some of these connections.

4.2.2. Multilayer network models.

A topic that has recently attracted considerable attention in physics and applied mathematics is the study of multilayer networks. The idea is that nodes simultaneously participate in multiple networks. For example, extending our trading example, suppose that a trader can trade profitably only if it has access to counterparties for two different assets, which trade in independent networks. Multilayer structure turns out to be another channel through which fragility can arise. Buldyrev et al. (2010) showed that, even if the setting is such that contagion in either network separately would have a continuous phase transition, functionality in the coupled network contagion process can disappear discontinuously as we vary x. Aymanns et al. (2020) develop this point in a trading network application.

4.3. Other Models of Complex Contagion

What distinguishes the simple contagion of the models in Section 4.1 from those in Section 4.2 is that the so-called local contagion condition in the latter section is complex. This term has a technical meaning in network theory: A contagion is called simple if, ex post of shocks, a node is activated (with the meaning, as usual, depending on the application) as long as at least one neighbor is. For example, in Section 4.1, a firm is functional if at least one of its suppliers is functional. Contagion rules not in this class are called complex. In contrast to Section 4.1, in Section 4.2 a firm is functional only when more than one of its suppliers are functional—at least one for each input required. Other models of complex contagion are considered in a large literature in networks. We now discuss several models of this type, highlighting some phenomena that are distinct from those we have been discussing but also relevant to issues of fragility.

4.3.1. Threshold coordination: homogeneous interaction.

Diagrams of the sort we have been studying play an important role in a related but different style of model, that of threshold contagion, introduced by Granovetter (1978). The basic idea of Granovetter's model is that there is a continuum population, with thresholds θ for taking an action—such as protesting against the government—with a cumulative distribution function F. Starting from a given number of initial adopters, at each time, the players whose thresholds are lower than the current number of adopters adopt the behavior. There is no explicit network in this model, but it can be thought of as representing a complete network in a large population where each agent is linked to all others and becomes active if and only if a fraction θ is active.

Supplemental Material >

Granovetter (1978) represented the myopic dynamic through a graphical approach that is closely related to the one discussed in Section 4.2. The role of $\mathcal{R}_x$ is played by the cumulative distribution function F, and staircase plots analogous to **Figure 5*a*** track the fraction of adopters at each stage and their convergence to equilibrium. We provide details in **Supplemental Appendix B**. There is a different type of fragility that manifests in this model, not due to the movement of F as we vary a parameter like x but rather due to its shape. Depending on the shape of F, there can be tipping points whereby the equilibrium selected is very sensitive to the initial conditions (indeed, the final outcome can vary discontinuously with the initial conditions). In contrast, in the exercise of letting supply chains get long in order to model complexity, the fixed point associated with the highest reliability was always selected as the relevant one in our study of complex production.

Jackson & Yariv (2007) extend Granovetter's model to incorporate heterogeneity in network connections as well. They study a network model where the only heterogeneity in network positions comes in the form of degrees (i.e., interaction is uniform given the degree distribution).

Rather than simply assuming a behavioral threshold model, Jackson & Yariv (2007) microfound behavior by specifying costs and benefits. They assume that the benefit of acting is increasing in the fraction of adopting neighbors, as does Granovetter, but it may also depend on one's degree (so that more popular people tend to enjoy the action more, for example). There is also a randomly drawn cost of adoption. This combination generates random thresholds for action (as in Granovetter 1978). Jackson and Yariv use the type of graphical analysis demonstrated above (along with mean-field assumptions for technical convenience) to derive subtle conclusions about comparative statics in network structure. Building on methods employed by Jackson & Rogers (2007), they study comparative statics in adding links (first-order dominance shifts of the degree distribution) and in making degrees more variable (mean-preserving spreads). These effects can make the fraction of individuals taking the action in equilibrium go in either direction, depending on the exact way in which benefits depend on degrees.

Within this broad framework, Blume et al. (2011) consider network contagion at the micro level without making use of the mean-field approximation. They investigate how the network structure matters when nodes' thresholds are drawn independently from a distribution. They find that this distribution of thresholds and the network structure interact in interesting ways. For example, small changes in the distribution can lead to large changes in which network structures minimize contagion. In particular, the optimal network structure can abruptly change from one containing many separate cliques to a tree. As discussed in Section 5, below, similar results are obtained in models of financial networks that incorporate balance sheet considerations.

4.3.2. Threshold coordination: local interaction.

Morris (2000) analyzes how a convention spreads through a network when agents myopically best-respond to neighbors' behavior in a two-action coordination game. The best-response behavior is given by a threshold rule, where an individual adopts a behavior as long as sufficiently many of its neighbors do. In contrast to the Granovetter threshold model, however, interaction is genuinely local. Morris characterizes conditions for the coexistence of conventions on a single connected network. These conditions boil down to a suitable notion of cohesiveness: A set of nodes can maintain an action different from its surroundings if each of its agents has a sufficiently high proportion of its connections within that set. However, the maintenance of different conventions can be fragile: A small number of agents changing behavior can set off a cascade of behavior changes in a large cohesive group (for a nice exposition, see Easley & Kleinberg 2010, chapter 19; for different analyses of the robustness and fragility of conventions that showcase a range of network-theoretic techniques, see Ellison 1993, Montanari & Saberi 2010). Though quite different in detail, the Morris model echoes some of the qualitative messages of Sections 4.2 and 4.3.1.

The contagion of behavior in a network involves people optimizing their behavior in reaction to what they see their neighbors do. This is related to contagion of strategic behavior in games of incomplete information, where a certain type of player optimizes against the expected behavior of types of opponents that he expects to encounter (Morris 1997, 2000). Thus, a convention such as "do not rebel against the incumbent regime" can be stable, but if public events slightly change the network or the preferences of a key set of agents, they can coordinate many agents on rebellion. Though a proper discussion of these issues is beyond our scope, we refer the interested reader to Chwe (2000) and Christensen & Garfias (2018) for more detailed bibliographies.

4.4. Discussion and Takeaways

We have considered several large-network models of contagion—of information, disease, distress, or some other state. Through a variety of methods, these can be made tractable; we have emphasized the graphical analysis of the $\mathcal{R}_x$ curve as a particularly useful tool. A rich set of theoretical questions, with immediate practical applications, concerns how and where the system is fragile. Does degradation happen gradually or abruptly? Which parameters is the system especially sensitive to?

We have shown in this section that the complexity of a production process—in the sense of requiring multiple inputs—can be a key driver of fragility. It changes the situation from one of continuous aggregate behavior, with the aggregate state changing gradually, to one with stark discontinuities. Other features, such as suitable heterogeneity in activation thresholds, can create distinct kinds of fragility.

Other research (e.g., Strogatz 2001, Dodds & Watts 2004, Centola & Macy 2007, Gai & Kapadia 2010) suggests that the complexity of network processes is related to their fragility. Complexity, of course, is an open-ended term: It can be interpreted as dependence on many counterparties at once, many networks, or simply heterogeneity of certain kinds in failure thresholds (as in Jackson & Yariv 2007). Such systems deviate from the simple contact processes discussed in Section 4.1 and have richer dependence on aggregate parameters. When they experience breakdowns, those breakdowns tend to be more dramatic or severe.

5. SUBSTITUTION AND INTENSIVE MARGINS

So far, we have focused on the extensive margins: which firms can operate in a fixed network. Both in the production setting and in financial networks, intensive margins and substitution are also important. In the context of production networks, for multisourcing to be most effective, suppliers should be flexible in how much quantity they can offer; capacity constraints or adjustment costs are therefore important. The possibilities for technological substitution are also important—for example, whether complex computer chips can be repurposed to perform simple tasks. In the context of financial networks, fungibility and substitution are clearly first-order considerations. On one hand, a bank may be able to use the value of healthy assets to compensate for failing ones; on the other hand, small losses from various sources might accumulate on a balance sheet to precipitate a failure. None of this is captured by simple discrete models of contagion of the type discussed above, where it is simply the number of counterparties in some state that is relevant.

While Section 4 built on Section 3 by letting networks become large and complex, in this section we build on Section 4 by considering more carefully the flexibility of production and the role it plays in fragility. This has important implications and leads to a variety of fundamentally different and important modeling approaches. We organize our discussion around three types of flexibility or limitations thereto: (*a*) the technological margin, such as whether firms can use more labor and less capital; (*b*) the intensive margin, namely whether existing suppliers can supply more; and (*c*) financial fungibility.

5.1. Technological Substitution

In production network models, it is standard to endow firms with technologies that allow for continuous substitutability between inputs. For example, a firm might be able to replace some workers with machines, substituting capital for labor. Thus, following a shock to an input, firms may adjust their technology choices to reflect the increased scarcity of that input—at least in the longer run. This is especially realistic when the model is thought of as representing aggregates, so that the nodes are industries.

Historically, the literature on production networks has allowed for equilibrium adjustments and hence incorporated substitution on these margins (Horvath 2000, Gabaix 2011, Acemoglu et al. 2012). (In contrast, so far we have focused on contagion of failure that happens in the shorter run, when substitution of this type cannot cushion it.) Standard models in this framework feature a network of interconnected production nodes—each with its own production function—in general equilibrium. The network is given by the reliance of various sectors on the inputs produced by other sectors. An important advantage of such models is that one can very naturally ask questions about aggregate production.

Early papers defined the systemic importance of a node as the amount of aggregate production lost when that node is hit by a small productivity shock. Acemoglu et al. (2012) show that this measure of systemic importance can be interpreted in terms of a certain network centrality statistic (Bonacich centrality) of the production network. More central sectors are those upon which a larger number of sectors rely directly and indirectly for inputs; disruption of such sectors is particularly consequential. Hulten's theorem offers an easy way to measure this centrality: It turns out to be simply proportional to the sector's total sales (Hulten 1978) and independent of other attributes, such as other aspects of its network position.

Supplemental Material >

Hulten's theorem yields some counterintuitive predictions. Practically speaking, it seems as if disruptions to some sectors have an impact far out of proportion to their size. For example, as discussed in Section 2.1.1 and **Supplemental Appendix A**, the shortage of basic commodity computer chips (costing a few cents) has disrupted many industries at great cost, despite representing a very low proportion of the value of such products. Evidence supports this observation: Baqaee & Farhi (2019) find that, in practice, sectors of similar sizes can matter very differently when they are disrupted.

Two key forces driving the stark Hulten's theorem results are that (*a*) the economy is able to immediately reequilibrate following a shock and (*b*) shocks are small, so nonlinearities can be neglected through a first-order approach to the analysis. However, in the practical motivations for studying fragility, evidently nonequilibrium phenomena, such as shortages, are a key feature.

Relatedly, nonlinearities seem to be important, with shutdowns being an especially stark example. We discuss nonlinearities first, followed by short-term effects during the period before the economy can reequilibrate.

Recent research has focused on marrying the tractability of the classic production networks model with firm shutdowns. Baqaee (2018) focuses on firm exit, which plays a role somewhat analogous to the role of liquidation in financial models. In a model with imperfect competition and external economies of scale, sectors that are not particularly central in the canonical first-order analysis can unleash cascades of failure. At a technical level, the extensive margin of exit is made tractable by studying a large industry and focusing on the mass of firms that are operating.

Subsequently, Baqaee & Farhi (2019, 2020) and Acemoglu & Tahbaz-Salehi (2020) developed models extending the network analysis of production to include nonlinearities, firm exit, and inefficiencies of many kinds. One way progress has been made is by refining local analysis (of reactions to shocks) through adding higher-order terms and demonstrating their quantitative significance. These additional terms can capture forces coming from shutdowns. Indeed, forces such as those presented in Section 4 can be brought into a macroeconomic framework via such models. This is an important frontier of research in this area.

An alternative benchmark to one in which the economy is assumed to perfectly reequilibrate following a shock is the opposite extreme, in which no adjustments to input shares are possible. Elliott & Jackson (2022) take a general equilibrium model of global supply networks and study this benchmark. Interestingly, the products for which short-run disruptions have a very big impact can be very different from the products that matter most in the longer run, when substitution can occur. While the value of the sales generated by a product (be it a final good or an intermediate good) is what matters in the long run (Hulten's theorem), in the short run what matters is the value of all sales of all consumer goods that use the affected good directly or indirectly. Thus, an immediate shortage of computer chips can have a quite limited long-run impact and, at the same time, a very big short-run impact.

5.2. Intensive Margins of Substitution

Implicit in the simple model in Section 3 is that multisourcing opportunities captured by the supply network define the constraints on using different suppliers whereas there are no constraints on the intensive margin: Each supplier can fulfill all demand. There we saw how the ability of a firm to produce varies with the extent of multisourcing, as well as the distribution of shocks and the structure of the supply network.

Limits on intensive margin adjustments can be incorporated into such a setting by including capacity constraints. When firms face such constraints, the ability of one supplier to compensate for shocks incurred by others is limited by its capacity, and shortages can occur. One way to model this scenario is to incorporate capacity constraints at the firm level (an intensive margin) with network constraints determining which firms can supply which others (an extensive margin).[18]

Capacity constraints can be used to capture new and interesting phenomena in substitution. For example, suppose a firm's production is disrupted. Whether a competitor firm can increase their production in response, mitigating the impact on aggregate output, might depend on whether parts that would normally be supplied to the disrupted firm can be rerouted to these competitors. In this and other ways, the nonlocal network structure can matter for understanding the impact of a shock.

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[18] It is also possible to limit the magnitude of transactions between specific firms if, for example, firms are willing to entrust only a limited-size order to a supplier they do not use very frequently.

An interesting question that can be asked in this context is which firms or groups of firms are critical to maintaining an economy's production. Carvalho et al. (2021a,b) show how critical firms/groups of firms (termed bottlenecks) can be found by reformulating the problem as a flow problem. This makes the flow of goods through a supply network analogous to the flow of a liquid through a given configuration of pipes, connecting the problem with an extensive applied mathematics literature. In **Supplemental Appendix C.3** we illustrate how this reformulation can be done for the simple supply networks considered in Section 3 and discuss how the flow problem approach allows supply networks to be analyzed at scale. Indeed, Carvalho et al. (2021a) apply this approach to data covering the near universe of business-to-business transactions in Uganda to construct and analyze the supply network for the Ugandan economy. In this way, a small number of firms are identified as bottlenecks for the Ugandan economy. Following a shock to other firms, inputs can be rerouted through the supply network without reducing overall production, but a shock to a bottleneck firm will reduce the productive capacity of the economy. For this reason, bottleneck firms are also those firms whose network position confers market power on them.

Supplemental Material >

5.3. Financial Networks

The simple model considered in Section 4.1.3 simplifies financial interdependencies into a simple viral contagion. In practice, a firm can fail because of large losses spilling over from a small number of counterparties, or smaller losses from a larger number of counterparties. A literature on financial networks, surveyed by Jackson & Pernoud (2021), has developed models in this direction. Incorporating the intensive margin allows us, for example, to vary the size of relationships—what fraction of a typical firm's assets depends on a counterparty's value. Nevertheless, the fundamental forces discussed in Section 4 continue to have an important bearing on the potential for failures to cascade and, hence, the impact that the financial network structure has on systemic risk.

Modeling the intensive margin requires keeping track of balance sheets and taking an accounting approach to distributing losses through the financial system. Doing so ties it into a finance literature on payment clearing—who pays what to whom in different states of the world (Eisenberg & Noe 2001, Rogers & Veraart 2013). There are also models of how a single loss can be counted on many balance sheets (Brioschi et al. 1989, Fedenia et al. 1994).[19] However, an important point in much of the recent research on financial networks is that in order to have interesting real implications, accounting models of this sort must be married to a model of discrete losses being generated by failures. Such "bankruptcy costs" might include asset liquidation costs, legal fees, and the inefficient allocation of affected resources; they are incurred when an organization's value falls below some threshold. Without failure generating some new costs, financial networks simply distribute the losses associated with shocks. Glasserman & Young (2015) formalize the idea that the potential damage done by cascades of failures is necessarily rather limited unless there are mechanisms that amplify losses as more failures occur.

Elliott et al. (2014) model the intensive margin deterioration of balance sheets, with discrete costs that erode value every time a financial institution fails, to study how network structure affects the fragility of the financial system. A key force governing whether cascades can propagate widely is whether there are sufficient connections. Indeed, the financial network undergoes a phase transition like those discussed in Section 4—as the network becomes sufficiently well connected, long chains of interconnection suddenly emerge, which are necessary for failures to propagate widely. Interestingly, though, when connections become sufficiently dense, the initial losses from shocks

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[19] It may be that if A loses value and B has a claim on A, then their combined book value goes down by more than the value initially lost by A.

are spread among enough financial institutions that a cascade does not occur. This nonmonotonicity is also present if we consider how integrated the financial system is—what fraction of a typical firm's value is dependent on others' solvency. The worst contagions happen at intermediate levels of integration.

Acemoglu et al. (2015) incorporate failure costs by positing that insolvent banks have to inefficiently liquidate their projects early. They show that the fragility of different financial systems depends critically on the size of shocks. Financial systems that are well connected are very robust to small shocks, because they diversify the shocks among many banks to avoid failures, but are also very fragile to very large shocks. In the case of very large shocks, the same financial connections that facilitated the diversification of small shocks provide a conduit for failures to propagate widely (we discuss this topic further in Section 6).

6. EFFICIENT AND ENDOGENOUS NETWORK STRUCTURES

It is often claimed that networked systems are too fragile. To make sense of this claim, we need a notion of a planner's problem to consider the structure of efficient networks, as well as a theory of equilibrium outcomes and incentive misalignments. This section highlights several insights concerning these problems, focusing on conceptual messages in stylized models. We first discuss basic theories of equilibrium network formation and the welfare implications in financial networks, then turn to supply networks, following the chronological development of these literatures. Finally, we discuss policy interventions.

6.1. Financial Networks

We begin by studying the problem of what constitutes an efficient financial network. Then, with that benchmark in hand, we consider the frictions that may prevent such network structures from forming.

6.1.1. Efficiency. Recall from Section 5.3 that when there are no failure costs, payment clearing simply represents transfers across agents—which limits the efficiency implications of the network structure.[20] However, introducing failure costs makes the network structure matter. If we assume that a planner seeks to maximize the overall net wealth in the system, this is equivalent to minimizing the expected aggregated failure costs.

Several recent publications formulate and solve social planners' problems where the planner chooses the structure of financial connections among banks (e.g., Acemoglu et al. 2015, Cabrales et al. 2017, Erol & Vohra 2018, Elliott et al. 2021a). Several general lessons have emerged from this literature.

First, the efficient structure of the network depends on the distribution of shocks. When a system is highly interconnected, losses are dissipated across many financial institutions, which can prevent any of them from reaching their respective failure thresholds. At the same time, strong connections create the risk of propagating cascades of failures when larger shocks hit. A large shock can be very damaging to such an interconnected system, causing a great many banks to fail, with the overall losses amplified by failure costs. As Haldane (2009) put it, such financial systems are "robust yet fragile." Acemoglu et al. (2015) examine this trade-off in detail, showing how the efficient structure of financial networks can change dramatically as the shock size changes. When

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[20] Indeed, with transferable utility, all allocations of losses and hence all network structures are equally efficient insofar as they generate the same total surplus.

shocks are small, the planner wants to make the network very interconnected to cushion shocks. When shocks are large, the planner prefers a very sparse network to limit the spread of shocks.

Second, Cabrales et al. (2017), Erol & Vohra (2018), and Elliott et al. (2021a) build on this foundation by considering more general shock size distributions. They show that a way to reap the benefits of financial connections while minimizing risks is to cluster banks into modular groups, with strong connections within the group but weak or no connections across groups. The strong connections within the group allow some of the benefits of financial connections to be realized—for example, diversifying specific risks that a financial institution faces—while the weak connections across groups mean that any cascades emanating from within a group are contained within that group. A more general lesson from this analysis is that socially optimal network structures will tend to limit the size of cascades.

6.1.2. Equilibrium choices and incentive misalignment. Financial networks give rise to the potential for distortions and inefficient choices. Without complete contracts and perfect pricing of risks, banks' choices—what proprietary positions to hold, what assets to trade, which other financial institutions to do business with—entail externalities. The wedge between private and social incentives has important implications for systemic fragility.

Although a full review of these implications is beyond our scope, we mention a few highlights. Acemoglu et al. (2015) show that banks have incentives to engage in too much lending and borrowing in equilibrium, failing to take into account the consequences their failures have for indirect borrowers. Elliott et al. (2021a) study risk-shifting, where networks are formed in the interest of shareholders and to the detriment of debt holders. They provide theory and evidence on how banks that have financial connections with one another are more likely to take on similar risks. Jackson & Pernoud (2019) study a model delivering this inefficiency, as well as excessive risk-taking by banks and underdiversification.

Farboodi (2017) analyzes incentive misalignments, centering the inquiry on the stylized fact that financial networks have a core–periphery structure. In this model, "investment banks" have investment opportunities while "noninvestment banks" do not. The noninvestment banks can raise funds from households, and debt contracts between banks then allow these funds to flow through the financial system. In equilibrium, a core–periphery structure emerges, with the investment banks at the core and funds flowing to them from the noninvestment banks. As the investments may fail, all banks are subject to counterparty risk, while the investment banks extract intermediation rents. This creates externalities, leading the core (investment) banks to be overconnected and the periphery (noninvestment) banks to be underconnected.[21]

6.2. Supply Networks

We begin by studying what efficient supply networks might look like. Then we move on to consider what supply networks will form in equilibrium.

6.2.1. Efficiency. A basic welfare question concerning supply networks is how complex they should be. When should an economy focus on relatively simple production technologies, and when should it choose more complex ones? Levine (2012) provides a simple model that captures this key trade-off. Within the context of simple supply networks, where a single input needs to be sourced from a single supplier at each stage of production, complexity is captured by the depth of

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[21] An alternative force that can give rise to core–periphery structures, even when banks are ex ante symmetric, is economies of scale. Economies of scale can occur via information, when trading relationships serve as a conduit for information as well as for facilitating trade (Babus & Hu 2017, Di Maggio et al. 2019).

the supply network.[22] While longer supply chains are more prone to failure, it is assumed that they also generate more valuable products. Trading off these two forces leads to an optimal amount of complexity. Longer chains are optimal when individual units' strength is greater, the value of more complex products is greater, and shocks are more positively correlated (because this increases the probability of the event that no firm is disrupted). As a result, it is more efficient for more advanced economies, with institutions that protect against negative shocks to choose more complex production technologies, which would be more volatile holding conditions fixed.[23]

Jones (2011) brings a macroeconomic perspective to these forces. Because of the complementarities throughout an economy, investment to improve only one dimension of production can have low marginal returns. Coordinated policies can be necessary to realize the benefits of available technologies. Liu (2019) presents a study of such policies from a production networks perspective.

A dramatic version of this point can be made by returning to our study of phase transitions, whereby small changes in the environment can cause a system to behave in qualitatively different ways. This can sometimes create the opportunity for a social planner to have a very large influence on the behavior of a system with relatively small interventions, especially when the aggregate production features a precipice, as in Section 4.2. Small, coordinated investments can take a supply network from being incapable of production to functioning with high probability. Even when the phase transition is only a continuous one, the marginal returns of coordinated investments in firm strength (x) go from zero to quite large abruptly. These points are developed by Elliott et al. (2022).

A distinct but related force creating fragility is globalization (Elliott & Jackson 2022). As trade costs fall, there is increasing pressure to locate industries together to exploit comparative advantages, while more supply networks become international. This means that disruptions in one country can simultaneously affect many supply networks. It also makes networks prone to shocks that affect transportation, such as congestion at shipping ports and trade wars (see Section 2). However, there is some countervailing political pressure to source from closer to home (*Economist* 2018). Models of fragility are needed to analyze the trade-offs involved.

6.2.2. Equilibrium choices and incentive misalignment. In the context of supply networks, firms take numerous endogenous actions to improve their reliability: maintaining precautionary inventories, multisourcing, investments in relationships, and search efforts to locate alternative suppliers. Firms may not have incentives to take these actions efficiently; indeed, they may even have incentives to decrease a system's robustness. For example, when firms can exploit the market power that their network position confers on them, they will want to occupy bottleneck positions. The extent to which firms are able to do so will depend on the environment, but it is immediately obvious that their incentives are not necessarily aligned with a planner's.[24] Furthermore, even when both a planner and a firm prefer a more robust system, their incentives will not typically be aligned. Consider a firm's incentives to invest in improving its own reliability. These investments confer a positive externality on others in the network—both upstream and downstream—creating a wedge between the incentives of the firm and a planner whenever the firm does not fully extract

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[22] As discussed in Section 3, an alternative interpretation posits a firm that must source different inputs, each from a single supplier, where failure to source one input results in production being disrupted.

[23] For comparative statics of volatility in supply network complexity, see Elliott et al. (2022, section III.B). Interestingly, there is evidence that, despite operating in more complex and volatile industries, advanced economies are less volatile overall (Lucas 1988, Koren & Tenreyro 2007).

[24] Relatedly, depending on the types of shocks, Amelkin & Vohra (2019) show that firms in a supply network can choose to form fragile networks because they benefit from more variable outcomes.

the value created by its investments (which is the case under many standard market structures). Bimpikis et al. (2019) explore this issue, finding that misaligned incentives can result in inefficient entry when entry decisions are endogenous.

Another source of incentive misalignment is that upstream firms might have incentives to source differently from the way that is desired by their customers downstream, an issue considered by Bimpikis et al. (2018). The upstream firm trades off two factors—the cost of obtaining the required input and the rents the firm will capture, conditional on being able to produce. The first force often pushes firms to use the same (most efficient) suppliers—creating the more fragile diamond-shaped networks discussed in Section 3. The second force can lead firms to seek out different suppliers so as to have a chance of operating when others are not. In general, the way firms manage this trade-off need not align with what a planner would prescribe. The timing of how prices are set is important. To take an extreme but sometimes realistic example, if firms cannot extract any extra rents when they are in a strong network position (e.g., by being the only available option for their customers), then they have little reason not to choose the same inputs as others, despite the fact that doing so contributes to systemic risk.

Finally, we can consider similar questions of firms' investment incentives within the model of Section 4.2 in complex and deep supply networks. Will profit-maximizing firms invest in their own strength and the strength of their supply relationships such that systemic fragility is avoided?[25] Elliott et al. (2022) show that, on the contrary, endogenous investments often result in supply networks that are much less reliable than is efficient, perched on the precipice of the reliability curve in **Figure 5**.

6.2.3. Internalizing externalities with contracts.

Agents' decisions have repercussions for systemic fragility, creating a variety of wedges between private and social incentives. Given that this means surplus is being left on the table, a natural question to ask is whether contracts can remedy the problem and induce efficient investments. In this section, we argue that doing so is not straightforward and that there may be fundamental obstructions to potential contractual solutions.

Let us start with the problem of a firm *i* trying to ensure the robustness of its upstream supply network. The robustness of all such upstream firms has a bearing on the disruptions *i* faces. The first possibility is that firm *i* contracts with all these firms directly. In practice, this is difficult to do when supply networks are complex. Firms often know little about their supply chains more than one or two levels upstream, and it is difficult for firms to learn more (Choi et al. 2021). This is in part because suppliers fear being replaced or seeing their bargaining position deteriorate. For example, if a firm learns where its supplier sources its inputs, it becomes much easier for the firm to enter (or threaten to enter) that upstream market and cut the supplier out of the deal. Such opportunistic behavior by counterparties can undermine the bargaining position of the supplier, leading it to receive less favorable terms, which in turn shapes firms' behavior (Helper et al. 2000).

In short, it is often impractical for producers with complex upstream supply networks to contract with all upstream firms. Moreover, even if they were to do so, efficiency would require externalities to be fully internalized. Such suppliers are often upstream in others' supply chains too, so very particular contracts may have to be written to create efficient upstream investment incentives. Moreover, the positive externalities from investments that improve supply network robustness can flow upstream as well as downstream, further complicating matters (Baqaee 2018).

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[25] Such investment takes many forms. They include management practices to avoid misunderstandings and maintain supply relationships as well as to maintain redundancy via inventories and backup suppliers.

It is also easier to contract on problems that can be anticipated. Generally, firms have a good handle on problems that arise frequently and can take actions that mitigate these issues. It is the (many) rare problems each of which happens infrequently that pose a challenge for contracting (Simchi-Levi et al. 2014).

While it is impractical to contract with all firms that affect a given firm *i*'s production and all their direct and indirect customers, one might hope that there is a way to achieve efficiency with some simple, decentralized mechanism. For example, perhaps it is sufficient for firms to simply contract on the reliability of their direct suppliers, which will then contract on the reliability of their direct suppliers, and so on. This might help somewhat, but limited liability can make it impossible for a firm to fully internalize the value of its reliability. Such wedges can interact to amplify distortions further upstream.

Finally, one might hope that competition will naturally internalize externalities. Suppose a firm sources a given component type from three suppliers, each capable of fully supplying the firm. If two of the three suppliers are unable to produce for one reason or another, the remaining supplier will find itself in a strong bargaining position and may be able to extract substantial rents.[26] These rents may create incentives for it to invest in being reliable when others are not—for example, by locating away from competitor suppliers, thus reducing the risk of a common shock hitting all three suppliers at once (see Section 3.2.2), or by sourcing from different firms, thereby avoiding diamonds in the network (see Section 3.2.3). However, such decisions are costly. Choosing to source from a different, higher-cost supplier increases production costs, while locating away from others might mean sacrificing positive agglomeration externalities. If disruptions are frequent, these drawbacks might be outweighed by the benefits, and a firm might find it worthwhile to separate itself from others in this way. However, for infrequent disruptions, patience, deep pockets, and even a willingness to suffer medium-term losses may be necessary. Therefore, in practice, there are substantial hurdles to efficient investment. There is ample evidence of short-termism in financing (e.g., Budish et al. 2015). Furthermore, competitive pressures to source cheaper inputs and improve margins are strong (Linton & Vakil 2021).

6.3. Policy Interventions

Endogenously formed networks may create inefficient risk, and there may be fundamental obstacles to overcoming this risk, motivating the consideration of other policy interventions. The first step is to better measure risk. This might involve, for example, developing stress tests that examine which cascades are most worrisome and whether systems are capable of containing them in practice. Banks in the USA and Europe are required to report their financial positions with one another, allowing the financial network to be mapped out, and then many shock scenarios are considered by the regulators. Stress testing can help identify financial institutions on which others heavily rely. These are institutions that, if they fail, are most likely to precipitate a cascade of failures. Such cascades can be halted by stopping the initial failure. This motivates formally identifying systemically important financial institutions and subjecting them to tighter regulations that make them more robust and less likely to fail. The 2010 Dodd–Frank Act in the USA makes provisions for such regulation; similar regulation has been enacted in the European Union.

While taking account of failure costs is crucial for understanding the efficiency of different network structures, doing so complicates how the payment system is cleared. In the absence of

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[26] Note that, in practice, suppliers seem to sometimes forgo such opportunities to extract rents (Uzzi 1997) as part of the relational contracts they have with customers.

failure costs, standard models yield a unique outcome (Eisenberg & Noe 2001); with failure costs there can be multiple consistent clearing payment vectors in which different firms fail (Rogers & Veraart 2013). An important assumption often made is that when there are multiple consistent clearing payment vectors, the one selected minimizes failures.[27] While it is certainly in the interest of policy makers to avoid the possibility of bad outcomes, this might be too optimistic. Jackson & Pernoud (2020) show that this multiplicity is tied to cycles in the financial network and analyze policies that can eliminate this multiplicity. Optimal interventions are computationally hard to find. Netting, or canceling out offsetting obligations between pairs or groups of banks, can be helpful for reducing the multiplicity when possible.[28]

In supply networks, as in financial networks, there can be systemically important firms. Governments might, in principle, seek to target systemically important industries or firms with actions that will avoid disruptions or mitigate their impact. Industrial policies, such as those implemented in Asian countries during the rapid growth of the 1980s and 1990s, sought reliability in addition to industry growth. The disruptions of the COVID-19 pandemic have stimulated policy interest in this area. Indeed, in the USA, the Biden Administration requested $50 billion in 2021 to strengthen the semiconductor industry against supply chain disruptions (Leary 2021).

7. CONCLUDING REMARKS

We conclude with some brief remarks and appeals for further research. First, our focus has been on fragility with respect to random exogenous shocks. An alternative and complementary question is to posit an adversary and seek robustness with respect to the adversary's actions. Such an analysis can be motivated in several ways. Most directly, there are settings in which an attack-and-defense perspective is natural. Hackers seek to exploit weaknesses in networked computer systems, while terrorists or adversarial governments might want to disrupt infrastructure networks, production networks, or financial networks. Alternatively, it can be fruitful to consider an ambiguity-averse regulator seeking to make a system robust with respect to a hypothetical adversary that can choose which shock hits. Interestingly, networks that are relatively robust with respect to random shocks can be very fragile with respect to targeted attacks (Albert et al. 2000).[29]

Second, the large-network fragility mechanisms surveyed in Section 4 have been developed in simple microeconomic models. It would be valuable to integrate such mechanisms into richer models, such as macroeconomic ones, where phenomena like price adjustment and substitution possibilities would interact with fragility in interesting ways. More broadly, an important frontier for future research is modeling how fragile supply networks interact with other markets and institutions—such as labor markets, government industrial policies, and logistics industries.

Finally, we have drawn many analogies between supply networks and financial networks. However, there is a notable difference regarding our knowledge of their structures. In the case of financial networks, a wealth of research has mapped out network structures across a variety of financial markets. These measurements are a cornerstone of many of the financial network papers we have cited, and they have invigorated the literature by, among other things, giving direction to theoretical research. The analogous knowledge base is largely missing for complex international supply

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[27] The set of consistent clearing payment vectors is such that there is one in which the only banks that fail are those that fail for all consistent clearing payment vectors.

[28] Often, financial institutions hold many different positions with one another in a variety of assets, which can make it netting substantially more difficult in practice than it may seem to be in simple models (which tend to abstract away from the details of positions).

[29] There are large literatures, spanning several disciplines, on attack-and-defense networks. For overviews and surveys covering a variety of perspectives, see Roy et al. (2010), Barabási (2013), and Dziubiński et al. (2016).

networks, and very few openly available data sources exist. Thus, we do not know enough about supply networks. Research providing a more rigorous understanding of the empirical structures of supply networks, how they differ across industries, and how such structures are stressed and changed by shocks would be very welcome.

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