The Changing Input-Output Network Structure of the U.S. Economy

By Andrew Foerster and Jason Choi

The U.S. economy is a collection of industries that produce different types of goods and services by varying means. These industries differ from one another not only in their output but also in the set of goods and services they use as inputs into their production processes. Manufacturing industries, for example, tend to be more dependent on refined raw materials than are services industries. But manufacturing industries also use services such as marketing as inputs, and service industries use manufactured goods such as computers as inputs. In this way, industries across the economy are linked through input-output relationships.

This network of input-output relationships has possibly important implications for how economic activity evolves—both over the business cycle and over the longer term—and for the conduct of monetary, fiscal, and regulatory policy. For example, productivity gains from technological progress or supply disruptions to one industry might spill over to industries that supply or demand intermediate inputs from the directly affected industry. The magnitude of these spillover effects may depend crucially on the number of links between the affected industry and others as well as the industry's importance within the network.

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In this article, we document how the input-output network structure of the U.S. economy has changed over time. We find that the number of connections between industries have changed over time but that these changes are not necessarily associated with the business cycle. In addition, we find that certain, usually services-based industries have become more important in the network over time.

Section I discusses why input-output networks might be relevant for understanding the macroeconomy. Section II illustrates different network configurations. Section III documents how the degree of interconnection has evolved over time as well as which industries have driven the trend. Section IV highlights the extent to which certain industries have become more or less important within the network.

I. The Importance of the Input-Output Structure for the Macroeconomy

Understanding the input-output structure of the economy and how this structure might vary over time can shed insight into macroeconomic fluctuations—in particular, how and to what extent shocks to specific industries might affect other industries through input-output relationships and thereby generate fluctuations in the entire economy.

At first glance, it is not obvious why considering industries as separate entities might provide any insight into the macroeconomy. A classic argument from Lucas suggests that industry-level shocks should cancel each other out—that is, some industries should get good shocks and others bad shocks—leaving the aggregate economy largely unaffected. As a result, only aggregate shocks that affect large numbers of industries should matter for the macroeconomy.

One reason why Lucas's argument might not hold is because industries tend to be linked by input-output relationships. In this alternative theory, studied extensively by Acemoglu and others (2012) and Carvalho, industries that receive shocks pass those shocks on to other industries that require their products as intermediate inputs. In other words, a shock to an industry affects other industries—and thereby the macroeconomy—by affecting the supply of inputs available to other industries and the demand for other industries' products. Hulten argues that only an industry's sales as a share of output matter for the transmission of shocks to the aggregate economy, whereas Baqaee and Farhi argue the exact network structure of the economy also matters.

The extent to which shocks to individual industries affect aggregate fluctuations is an empirical question. Foerster, Sarte, and Watson find that for the set of industries that make up industrial production (IP), shocks to individual industries account for half of the fluctuations in the aggregate IP measure. Atalay argues that industry shocks may in fact be more important due to producers' inability to easily substitute across inputs. And Acemoglu, Ozdaglar, and Tahbaz-Salehi point to input-output linkages as important drivers of large fluctuations.

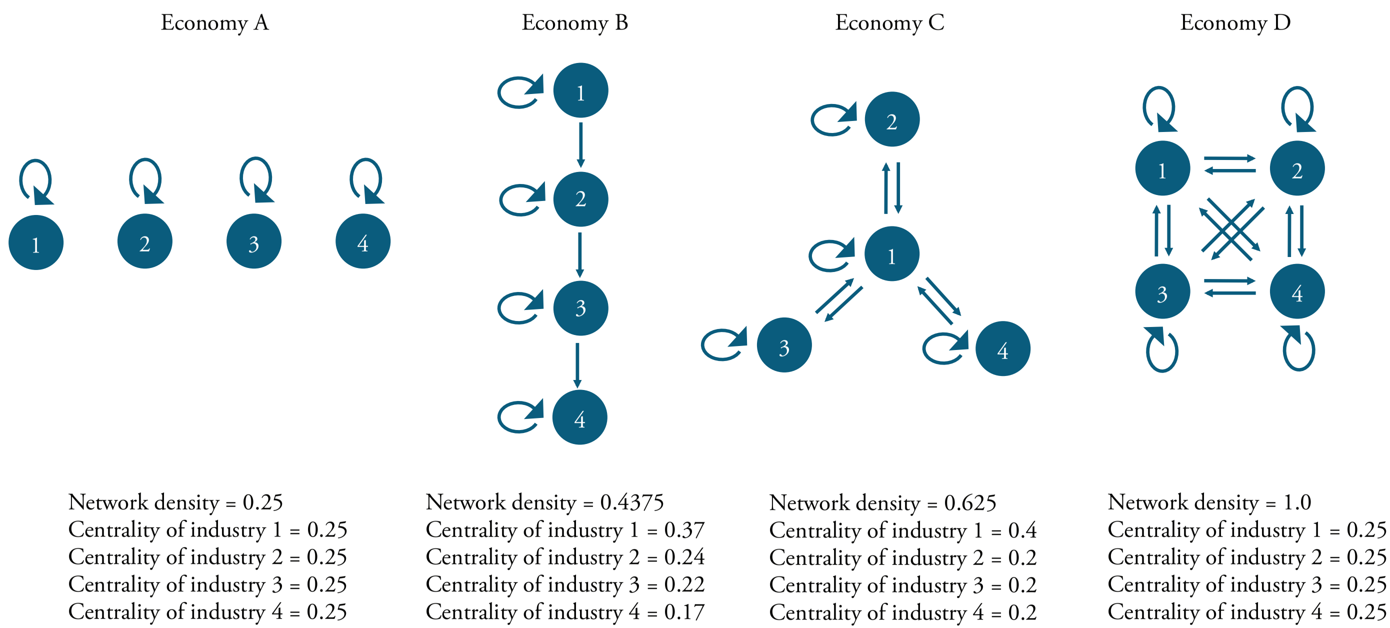
At the same time, the importance of input-output linkages may vary, as the input-output structure of an economy changes over time with technology, competitive pressures, and other factors. Long-term productivity trends can alter the types of final goods consumed in the economy, which in turn affect the input-output relationships between industries. In addition, firms within each industry may change their input bundles over time, perhaps by substituting different goods in the production process or choosing to produce inputs within the firm rather than obtaining inputs externally (Oberfield). These decisions at a firm or industry level determine the exact structure of the network at a given point in time.[1]

Identifying the structure of the input-output network is a crucial first step to any policy intervention. If advancements in technology hit industries and propagate throughout the network, the resulting outcomes could be perfectly natural and economically efficient, rendering policy interventions inappropriate. However, if financially constrained industries receive negative shocks, these shocks may cause outsized and inefficient downturns in the rest of the economy, thereby providing scope for policy to intervene to limit downturns (Bigio and La'O). This same reasoning motivated interventions during the financial crisis.

II. The Input-Output Network Structure of the U.S. Economy

To identify the network structure of the U.S. economy, we must first account for the various input-output relationships between industries. Figure 1 illustrates four simple examples of possible network structures.[2] In each example, the industries 1 through 4 produce

Figure 1
Network Structures of Four Example Economies



outputs, supply their own inputs, and possibly use each other's products as inputs. The figure shows each industry as a "node" and each existing input-output relationship as a directed "edge" or "link" representing the flow of goods.

Each example economy has a different network structure. Economy A has essentially no network: all industries operate independently and have no links between them. Economy B has a very direct supply chain: industry 1 produces inputs for industry 2, industry 2 supplies industry 3, and industry 3 supplies industry 4. Economy C has a star or hub-and-spoke network, where industry 1 supplies industries 2, 3, and 4, but those industries also supply industry 1. Finally, Economy D is completely interconnected: each industry supplies inputs to all others. These simple examples illustrate how the network structure depends on how different industries use inputs from other industries.

The examples in Figure 1 also highlight how different network structures affect both the degree of interconnection between industries and the importance or "centrality" of each industry within the entire network. Determining the degree of interconnection is relatively simple: Economy A, for example, is clearly the least interconnected, since it has no links between industries. In contrast, Economy D is the most interconnected, since all industries are linked to each other as both suppliers and demanders of inputs. Evaluating the relative importance or centrality of each industry to the network as a whole is more challenging, as the illustrations reveal little about the strength or magnitude of each link. Nevertheless, none of the industries look more central than the others in Economies A and D. Economy C, on the other hand, has a very important industry, industry 1, that both supplies products to and demands products from the other industries as the main hub in the hub-and-spoke system.

The example economies' structures—together with their industries' varying degrees of interconnection and centrality—reveal how shocks to different industries might propagate across the network. In Economy A, a shock to any one industry will not spill over to the other industries. In Economy B, each industry is part of a single vertical supply chain, so a shock to industry 4 will have no supply spillover effects (since industry 4 supplies no inputs to other industries), but will have demand spillover effects (since industry 4 demands inputs from industry 3). In contrast, a disturbance to industry 1 will have supply effects on every industry in the economy.

In Economy C, industry 1 supplies inputs to all other industries, which are otherwise unconnected. Because industry 1 is connected to every other industry, a shock to industry 1 will have economy wide effects. Furthermore, industry 1 may receive second-order disturbances, as the affected industries supply inputs back to industry 1. In this way, shocks to industry 1 become amplified, and even shocks originating from the peripheral industries can ripple through the entire economy. Lastly, in Economy D, the industries are completely interconnected, making the effects of shocks somewhat ambiguous. Shocks to industry 1 will tend to affect the other three industries directly through the links—but as the network is not overly dependent on one industry, the shocks may not propagate to the extent they would in the supply chain or hub-and-spoke economies.

Data on the U.S. input-output structure

To transform our example economies from theoretical illustrations to practical models, we use data from the Bureau of Economic Analysis (BEA) on the flow of goods from each industry in the U.S. economy to other industries. When aggregated, these industries as defined by the BEA sum to gross domestic product, and thus cover the entire economy. The data are available at an annual frequency and show the dollar value of goods produced, for example, in industry *i* that industry *j* uses as inputs. We then normalize the resulting table so that entries are in shares of the demanding industry, so for a given industry *j*, the flows from all industries *i* sum to 1.[3] In other words, the *(i,j)* entry in our final table lists the fraction of inputs for industry *j* that come from industry *i*, and we construct this table for every year in our sample.

The BEA provides input-output data that allow us to analyze the U.S. economy over a long time span at an annual frequency. The sample period is 1947 to 2015. At the beginning of the sample, the BEA defined 46 industries; in 1963 and 1997, the BEA revised its data collection techniques and defined 65 and 71 industries, respectively. Both increases in the number of industry definitions came through a direct disaggregation of existing industries. Therefore, for the first subsample of 1947–62, we have input-output data for 46 industries; in the second subsample of 1963–96, we have data for 65 industries but can also aggregate several industries back into their original 46 industry definitions; similarly, in the third subsample of 1997–2015, we have data for 71 industries but can combine industries back into their original 46 industry definitions.

The disaggregated industry definitions can shed light on the evolving input-output network structure of the U.S. economy. Table 1 lists the full set of industries in each of the subsamples to show which industries were and were not disaggregated. Several industries, such as "farms" and "forestry, fishing, and related activities" had no definitional changes. But "transportation and warehousing" was disaggregated into eight separate industries in 1963: "air transportation," "rail transportation," "water transportation," "truck transportation," "transit and ground passenger transportation," "pipeline transportation," "other transportation and support activities," and "warehousing and storage." As the results later in the article will show, the splitting of the transportation industry highlights that different types of transportation have become more central to and connected in the network over time.

Graphs of the U.S. input-output network

The BEA input-output data can generate graphs of the network of the U.S. economy that are analogous to those shown in Figure 1. Of course, the U.S. economy comprises far more than four industries, so the graphs using the BEA data are much more complex. Figures 2 and 3 show the network structure of the U.S. economy in 1947 and 2015, respectively.[4] Many different algorithms can be used to generate these graphs, and each conveys different information about the network. The algorithm we use tends to place more connected industries toward the center of the graph.[5] The size of the node indicates the relative importance of each industry for GDP, while the links between nodes indicate connections between industries. In addition, the links are weighted so that heavier lines represent larger flows of inputs and lighter lines represent smaller flows.

Comparing the 1947 and 2015 graphs highlights several changes in the network structure of the U.S. economy over time. First, the placement of industries within each graph shows their connections to other industries as well as how these connections have changed over

Table 1
Industry Definitions

1947–62 Breakdown		1963–96 Breakdown		1997–2015 Breakdown	
111CA	Farms	111CA	Farms	111CA	Farms
113FF	Forestry, fishing, and related activities	113FF	Forestry, fishing, and related activities	113FF	Forestry, fishing, and related activities
211	Oil and gas extraction	211	Oil and gas extraction	211	Oil and gas extraction
212	Mining, except oil and gas	212	Mining, except oil and gas	212	Mining, except oil and gas
213	Support activities for mining	213	Support activities for mining	213	Support activities for mining
22	Utilities	22	Utilities	22	Utilities
23	Construction	23	Construction	23	Construction
321	Wood products	321	Wood products	321	Wood products
327	Nonmetallic mineral products	327	Nonmetallic mineral products	327	Nonmetallic mineral products
331	Primary metals	331	Primary metals	331	Primary metals
332	Fabricated metal products	332	Fabricated metal products	332	Fabricated metal products
333	Machinery	333	Machinery	333	Machinery
334	Computer and electronic products	334	Computer and electronic products	334	Computer and electronic products
335	Electrical equipment, appliances, and components	335	Electrical equipment, appliances, and components	335	Electrical equipment, appliances, and components
3361MV	Motor vehicles, bodies and trailers, and parts	3361MV	Motor vehicles, bodies and trailers, and parts	3361MV	Motor vehicles, bodies and trailers, and parts
3364OT	Other transportation equipment	3364OT	Other transportation equipment	3364OT	Other transportation equipment
337	Furniture and related products	337	Furniture and related products	337	Furniture and related products
339	Miscellaneous manufacturing	339	Miscellaneous manufacturing	339	Miscellaneous manufacturing
311FT	Food and beverage and tobacco products	311FT	Food and beverage and tobacco products	311FT	Food and beverage and tobacco products
313TT	Textile mills and textile product mills	313TT	Textile mills and textile product mills	313TT	Textile mills and textile product mills
315AL	Apparel and leather and allied products	315AL	Apparel and leather and allied products	315AL	Apparel and leather and allied products
322	Paper products	322	Paper products	322	Paper products
323	Printing and related support activities	323	Printing and related support activities	323	Printing and related support activities
324	Petroleum and coal products	324	Petroleum and coal products	324	Petroleum and coal products
325	Chemical products	325	Chemical products	325	Chemical products
326	Plastics and rubber products	326	Plastics and rubber products	326	Plastics and rubber products

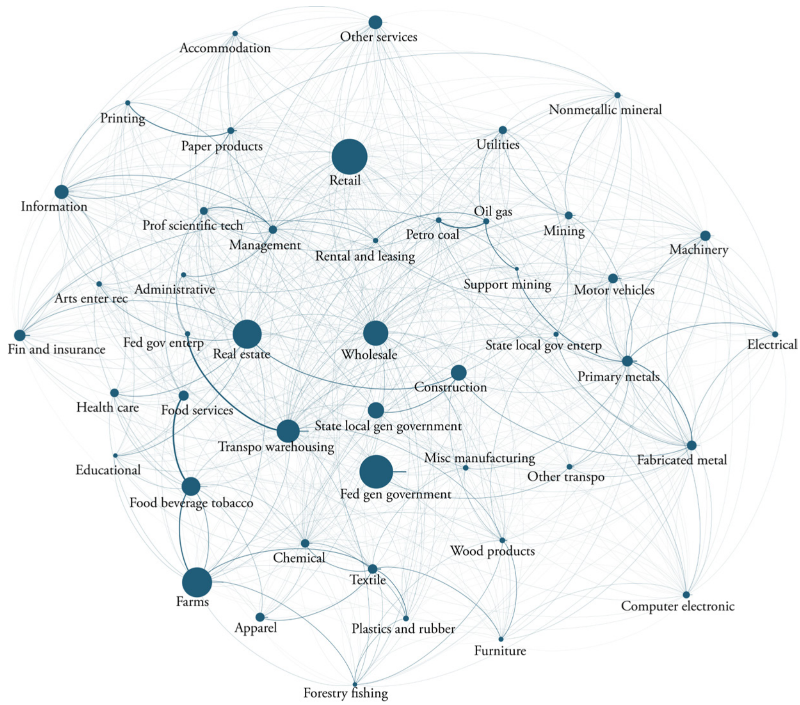
1947–62 Breakdown		1963–96 Breakdown		1997–2015 Breakdown	
42	Wholesale trade	42	Wholesale trade	42	Wholesale trade
44RT	Retail trade	44RT	Retail trade	441	Motor vehicle and parts dealers
				445	Food and beverage stores
				452	General merchandise stores
				4A0	Other retail
48TW	Transportation and warehousing	481	Air transportation	481	Air transportation
		482	Rail transportation	482	Rail transportation
		483	Water transportation	483	Water transportation
		484	Truck transportation	484	Truck transportation
		485	Transit and ground passenger transportation	485	Transit and ground passenger transportation
		486	Pipeline transportation	486	Pipeline transportation
		487OS	Other transportation and support activities	487OS	Other transportation and support activities
		493	Warehousing and storage	493	Warehousing and storage
51	Information	511	Publishing industries, except internet (includes software)	511	Publishing industries, except internet (includes software)
		512	Motion picture and sound recording industries	512	Motion picture and sound recording industries
		513	Broadcasting and telecommunications	513	Broadcasting and telecommunications
		514	Data processing, internet publishing, and other information services	514	Data processing, internet publishing, and other information services
52	Finance and insurance	521CI	Federal Reserve banks, credit intermediation, and related activities	521CI	Federal Reserve banks, credit intermediation, and related activities
		523	Securities, commodity contracts, and investments	523	Securities, commodity contracts, and investments
		524	Insurance carriers and related activities	524	Insurance carriers and related activities
		525	Funds, trusts, and other financial vehicles	525	Funds, trusts, and other financial vehicles
531	Real estate	531	Real estate	HS	Housing services
				ORE	Other real estate
532RL	Rental and leasing services and lessors of intangible assets	532RL	Rental and leasing services and lessors of intangible assets	532RL	Rental and leasing services and lessors of intangible assets

Table 1 (continued)

1947–62 Breakdown		1963–96 Breakdown		1997–2015 Breakdown	
54	Professional, scientific, and technical services	5411	Legal services	5411	Legal services
		5415	Computer systems design and related services	5415	Computer systems design and related services
		5412OP	Miscellaneous professional, scientific, and technical services	5412OP	Miscellaneous professional, scientific, and technical services
55	Management of companies and enterprises	55	Management of companies and enterprises	55	Management of companies and enterprises
56	Administrative and waste management services	561	Administrative and support services	561	Administrative and support services
		562	Waste management and remediation services	562	Waste management and remediation services
61	Educational services	61	Educational services	61	Educational services
62	Health care and social assistance	621	Ambulatory health care services	621	Ambulatory health care services
		622HO	Hospitals and nursing and residential care facilities	622	Hospitals
				623	Nursing and residential care facilities
		624	Social assistance	624	Social assistance
71	Arts, entertainment, and recreation	711AS	Performing arts, spectator sports, museums, and related activities	711AS	Performing arts, spectator sports, museums, and related activities
		713	Amusements, gambling, and recreation industries	713	Amusements, gambling, and recreation industries
721	Accommodation	721	Accommodation	721	Accommodation
722	Food services and drinking places	722	Food services and drinking places	722	Food services and drinking places
81	Other services, except government	81	Other services, except government	81	Other services, except government
GFG	Federal general government	GFG	Federal general government	GFGD	Federal general government (defense)
				GFGN	Federal general government (nondefense)
GFE	Federal government enterprises	GFE	Federal government enterprises	GFE	Federal government enterprises
GSLG	State and local general government	GSLG	State and local general government	GSLG	State and local general government
GSLE	State and local government enterprises	GSLE	State and local government enterprises	GSLE	State and local government enterprises

Source: Bureau of Economic Analysis.

Figure 2
The U.S. Input-Output Network in 1947

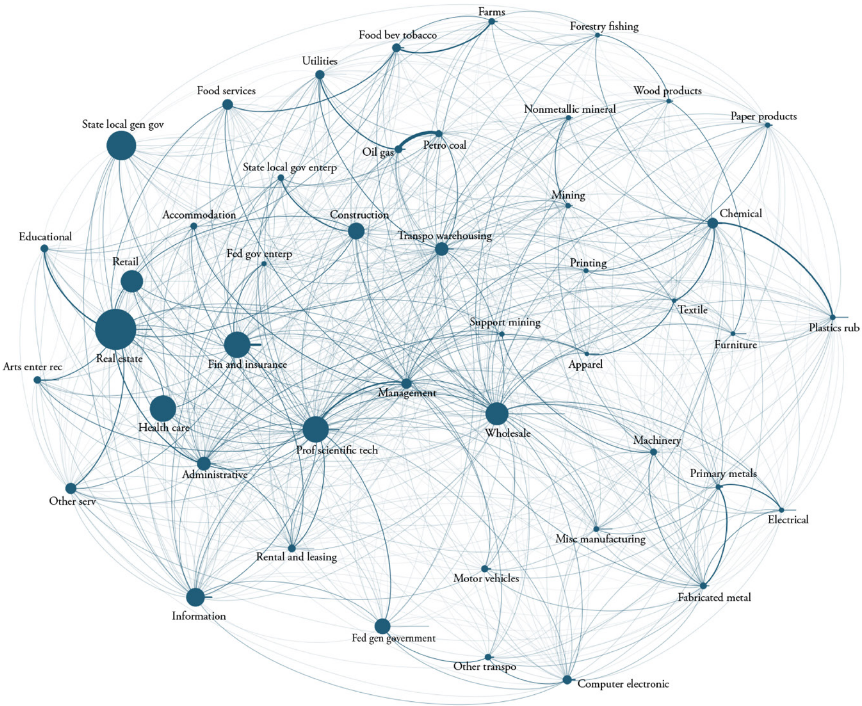


Sources: Bureau of Economic Analysis and authors' calculations.

the sample period. For example, "federal general government" sits near the middle of the 1947 graph, but moves near the outer ridge (approximately six o'clock) of the 2015 graph, suggesting its links to other industries have decreased over time. Other industries, such as "nonmetallic mineral products," are near the outer ridge (around one o'clock) in both graphs, suggesting the industry is less connected at both points in time. Second, the node size shows the importance of industries as contributors to GDP as well as their relative decline or growth over time. For example, "farms" has a large node in 1947, indicating it was relatively important to final GDP. However, the same industry has a very small node in 2015 (12 o'clock), suggesting farms have become less important to GDP over the sample period.

Third, given the complexity of the graphs, it is not clear which graph is more connected, nor is it easy to pick out how important

Figure 3
The U.S. Input-Output Network in 2015



Sources: Bureau of Economic Analysis and authors' calculations.

various industries are to the overall network. Fourth, some industries have very large flows of inputs between them, while others have much smaller flows. In particular, there are strong, obvious links between industries such as "farms" and "food and beverage and tobacco products," or between "oil and gas extraction" and "petroleum and coal products"; other industries have weaker but perhaps still important links.

In addition, portions of Figures 2 and 3 are similar to the simple examples in Figure 1. In particular, several subgraphs of the 2015 graph—or portions of the entire network graph—look similar to the example economies. For example, the thick lines indicate that "farms" supply important inputs to "food and beverages and tobacco products," which in turn supply major inputs to "food services and drinking places." These industries are similarly organized to the supply-chain structure of Economy B. In another example, "wholesale" trade is situated near the center of the graph with links going out to several industries, mimicking the central industry in Economy C. However, the graphs for both 1947 and 2015 in their entirety are more complex and thus not easily captured by the examples in Figure 1.

III. How Has the Interconnectedness of the U.S. Economy Changed?

Although the graphical analysis can reveal important features of the input-output network of the U.S. economy, the graphs cannot quantify the interconnectivity and centrality of individual industries. To measure these concepts more rigorously and in further detail, we next examine the network density of the U.S. economy and how that density has changed since 1947.

Network density as a measure of interconnectedness

Network density is a way of measuring the degree of interconnection in a graph or network. Specifically, network density describes the ratio of actual links between nodes to all possible links between nodes. Network density can vary between 0 and 1, with 0 implying no connections between industries and 1 indicating that all industries are connected. In our analysis, network density measures the fraction of possible input-output relationships that arise in a given year. As firm composition or technology changes over time, supplier links between industries may appear or disappear.

The example economies from Figure 1 can highlight how network density changes with different network structures. With only four industries, the number of possible links is relatively easy to enumerate: there are four possible own-input providers, and each industry has three possible outgoing links to other industries and three possible incoming links from other industries. Thus, an economy with four industries has $4^2=16$ possible links; more generally, an economy with N industries has N^2 possible links. In Economy A, the various industries are unconnected, and each industry supplies its own input bundle. Thus, the economy has four links, and the network density is $4/16=0.25$. Economy B has seven links and a resulting network density of 0.4375, while Economy C has 10 links and a density of 0.625. Finally, Economy D, which has all 16 possible links, has a network density of 1.

For any given network, a network density closer to 1 implies a more interconnected network, while a density closer to 0 implies a less interconnected network. In the context of an input-output network, a higher network density implies that industries tend to use inputs produced by a wider range of industries. As a result, shocks to individual industries are more likely to propagate to other industries in more dense networks.

The network density of the U.S. economy

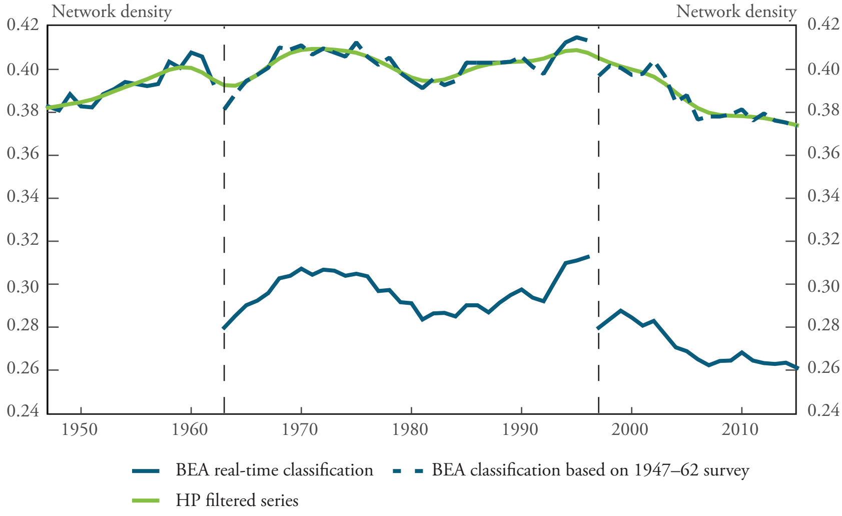
The network density of the U.S. economy has varied over time. Chart 1 plots two measures of network density from 1947 to 2015: one using a dataset that maintains the original 46 industries throughout the entire sample and one using more detailed data from 1963 to 1996 and from 1997 to 2015. Both the measure using the original 46 industries and the measure that uses more detailed data are below 0.5 throughout the sample, suggesting that less than half of all possible input-output relationships between industries actually materialize.

Using the measure that maintains the original set of 46 industry definitions, the average network density throughout the sample is 0.396, which highlights that slightly fewer than two out of every five possible input-output relationships between industries are present in any given year. With 46 industries, this density implies that 838 out of 2,116 possible links between industries are present each year. However, even at this level of aggregation, the number of links varies over time. The network density has a standard deviation of 0.01, which represents roughly 24 links. Thus, while the degree of interconnectedness in the U.S. economy has varied, this variation is relatively small.

The measure using the disaggregated industry definitions suggests that changes in data collection affect the measure of network density. In the first subsample with 46 industries from 1947–62, the average network density is 0.393; in the second subsample with 65 industries from 1963–96, the average network density is 0.296; and in the third subsample with 71 industries from 1997–2015, the average network density is 0.271. These figures highlight that as industry definitions change and the number of possible links grows, the number of actual links between industries does not grow proportionally with them.

The segments of the figures generated for the industry disaggregations in 1963 and 1997 suggest network density dropped during these years

Chart 1
Changing Network Density



Sources: Bureau of Economic Analysis and authors' calculations.

because the disaggregated industries were relatively less connected with the rest of the network. For example, the industry list in Table 1 shows that in 1963, "finance and insurance" was split into four different industries: "Federal Reserve banks, credit intermediation, and related activities," "securities, commodity contracts, and investments," "insurance carriers and related activities," and "funds, trusts, and other financial vehicles." The graph generated by the input-output links between only these four industries (not shown) indicates a very high network density of around 0.8 to 0.9—these newly defined industries were highly interconnected, as they supplied inputs to one another. A similar pattern holds for other disaggregated industries. An analysis of the various subgraphs allows us to rule out the idea that the drop in overall network density was due solely to a drop in connections between either newly defined industries or existing industries. Instead, the reason for the drop in the overall network density as seen in Chart 1 is likely because the newly defined industries tend to be less connected with other, dissimilar industries than they are with each other. Disaggregating industries consistently lowers measures of interconnectedness.

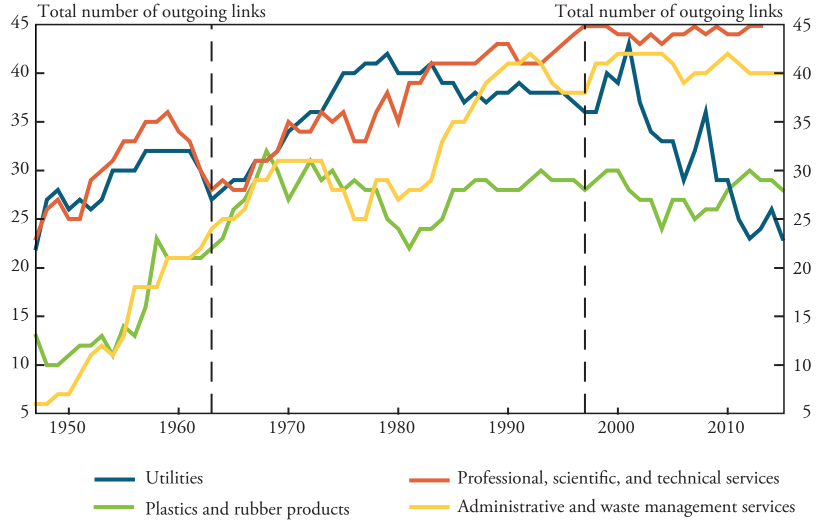
Beyond the level shifts, the annual variations in the network density of the U.S. economy show distinct trends over time. Using the network series for 46 industries, we fit a trend to the density data using the Hodrick-Prescott filter. This procedure identifies distinct time periods over which the network density either trended up or trended down. In particular, the network density trended up from 1947 to 1960, fluctuated around a constant level from 1961 until 1995, and then decreased over the final 20 years of the sample. These trends, which reflect a variety of factors such as firm composition within industries and technological progress that alters the input bundles required for given products, move at a lower frequency than the business cycle and do not have turning points that correspond to National Bureau of Economic Research (NBER) expansion or recession dates. In this way, the interconnectivity of the input-output network appears to trend at a longer cycle than the business cycle.

An analysis of which industries gained or lost links may help identify the driving forces behind trends in network density over time. Chart 2 shows changes in the number of outgoing links associated with four industries that largely accounted for the initial positive trend in the network density. In particular, the "administrative and waste management services" and "plastics and rubber products" industries both had dramatic increases in their links to other industries. Similarly, the number of output connections in the "professional, scientific and technical services" and "utilities" industries also increased. All four of these industries, then, became more heavily connected with other industries as input suppliers.

In contrast, Chart 3 shows the industries that lost the most links in the last part of the sample (1995–2015), during which network interconnectivity trended down. Seven primary industries lost links over this period, with the largest losses coming from "utilities," "other services, except government," and "federal government enterprises." All the industries shown in Chart 3 became less connected with other industries as suppliers, leading to a downward trend in overall network density in the latter part of the sample.

Chart 2

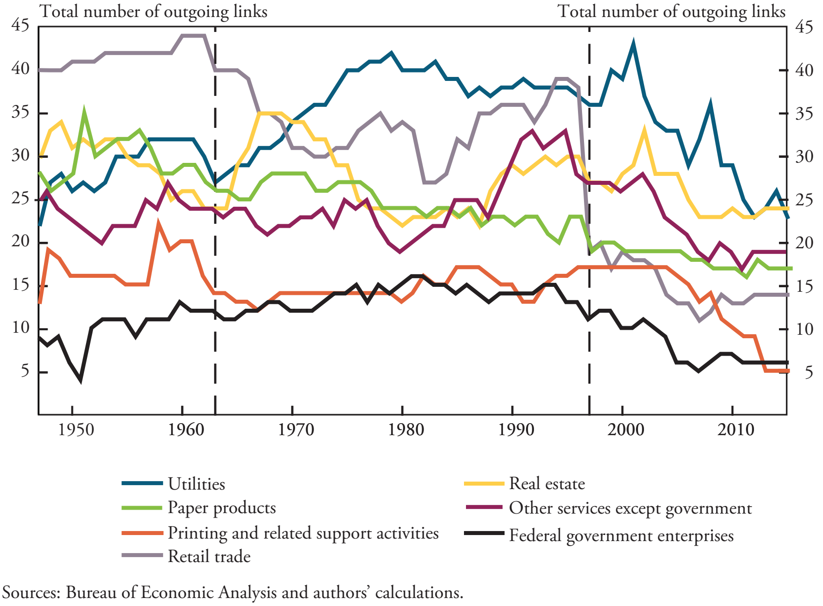
Change in Number of Links for Select Industries: Explaining the Rise in Network Density from 1947 to 1962



Sources: Bureau of Economic Analysis and authors' calculations.

Chart 3

Change in Number of Links for Select Industries: Explaining the Fall in Network Density from 1997 to 2015



Sources: Bureau of Economic Analysis and authors' calculations.

IV. Which Industries Have Become More Central to the U.S. Economy?

The network density of the U.S. economy's input-output relationships has changed over time, due both to changes in data collection that disaggregated individual industries into multiple smaller industries less connected to the overall economy and to low-frequency cyclical trends as specific industries became more or less connected over time. Measuring network density can shed some light on the extent to which shocks to various industries are likely to propagate throughout the economy through input-output linkages. One possible shortcoming of this approach, however, is that measures of network density consider only the presence of a link between two industries and not that link's relative strength or weakness. To assess which industries are most important in the network, we next examine a measure of network "centrality" and how it has changed over the sample.

Centrality as a measure of relative importance

Centrality is one way of measuring the relative importance of each node—specifically, each industry—in a graph or network. Centrality as a measure takes into account not only an industry's connections to other industries but also the strength of these connections and how connected the other industries are. In other words, centrality takes into account both direct and higher-order connections. In this way, an industry will tend to have a high measure of centrality if it is connected to other industries with high centrality.[6] Our centrality measure for an industry ranges from 0 and 1 and sums to 1 across all industries. The centrality of an industry thus indicates the relative influence it has over the entire network; for example, an industry with a centrality of 0.5 has twice as much influence as an industry with a centrality of 0.25.

The example economies presented in Figure 1 highlight how the centrality of industries can differ depending on the network structure. In Economy A, the independence of all four industries implies all are equally central, and the centrality measure is thus 0.25. Likewise, if we assume that all links in Economy D are equally weighted, then all industries are equally dependent on one another and their centrality measures are the same at 0.25. In Economy B, the vertical supply chain implies that industry 1 has the highest centrality, since it represents the beginning of the supply chain. Lastly, in Economy C, the hub-and-spoke or star network again implies that industry 1 has the highest centrality, since it provides inputs to and receives inputs from all other industries. Because of its centrality, shocks to the main hub industry 1 are likely to have larger effects across the network than shocks to any of the other industries.

The centrality of industries in the U.S. economy

We perform a similar assessment on industries in the U.S. economy to determine which industries have become more central—and thus more important—in the network over time. Table 2 shows the most and least central industries at the beginning and end of the full 1947–2015 sample along with those that fell or rose in centrality the most. Only two of the top five most central industries in 1947 remained in the top five in 2015: "transportation and warehousing" and "wholesale trade." The three other most central industries in 1947—"farms," "food and beverage and tobacco products," and "primary metals"—were replaced with "professional, scientific, and technical services," "finance and insurance," and "administrative and waste management services." The industries with the biggest rank declines were food or manufacturing related, while those with the biggest rank increases were services based or computer or plastics products. These changes all point to a shift in the importance of certain industries—not from a final product perspective, but in terms of input-output relationships.

Looking at changes in centrality at an annual frequency provides a more nuanced view of how industries have changed in importance over time. Chart 4 plots the centrality measures for a select group of industries over time. Panel A highlights four industries that increased in centrality throughout the sample. Of these four, "administrative and waste management services" and "professional, scientific, and technical services" saw the largest gains in centrality. Both industries had low centrality scores in 1947, but are now among the most central industries, meaning many more industries directly and indirectly rely on them for their own production processes. "Finance and insurance" also became much more central over the sample period, especially around the early 2000s. "Real estate" became very central during the late 2000s, likely

Table 2
Industry Centrality and Changes in Centrality from 1947 to 2015

Top 5 central industries in 1947	Top 5 central industries in 2015
Transportation and warehousing	Professional, scientific, and technical services
Primary metals	Finance and insurance
Wholesale trade	Administrative and waste management services
Food and beverage and tobacco products	Wholesale trade
Farms	Transportation and warehousing
Bottom 5 central industries in 1947	**Bottom 5 central industries in 2015**
State and local government enterprises	Educational services
Furniture and related products	Furniture and related products
State and local general government	Apparel and leather and allied products
Health care and social assistance	Support activities for mining
Educational services	Health care and social assistance
Top 5 rank improvements from 1947–2015	**Top 5 rank decline from 1947–2015**
Administrative and waste management services	Textile mills and textile product mills
Computer and electronic products	Farms
Rental and leasing services and lessors of intangible assets	Paper products
Plastics and rubber products	Food and beverage and tobacco products
Professional, scientific, and technical services	Miscellaneous manufacturing

Sources: Bureau of Economic Analysis and authors' calculations.

due to the housing bubble and ensuing financial crisis. However, both "finance and insurance" and "real estate" have decreased in centrality since the 2000s and returned to levels last seen in the 1990s.

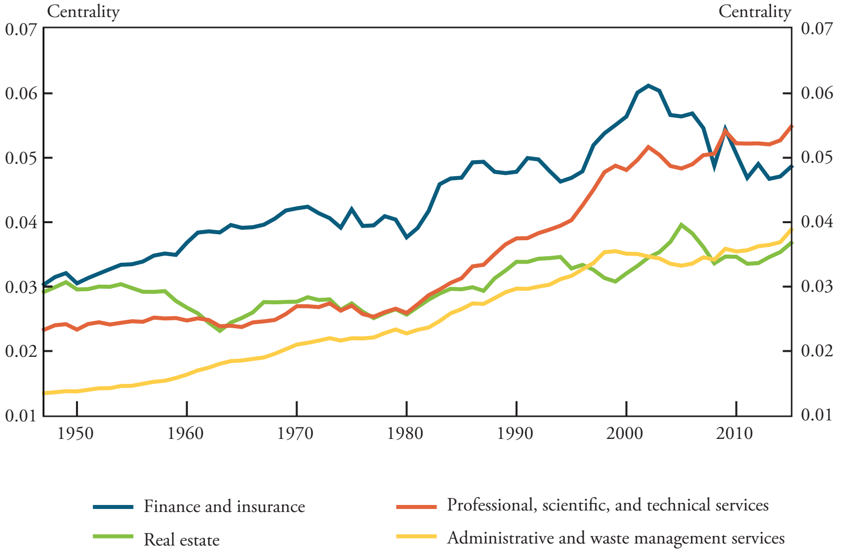
Panel B shows select industries that did not see substantial gains in centrality. For example, the centrality of "wholesale trade" has remained consistent throughout the sample period, while the centrality of "petroleum and coal products" spiked during the 1980s but had a relatively similar level at the beginning and end of the sample. Other industries, such as "primary metals" and "transportation and warehousing" have slowly become less central in the economy. Lastly, "health care and social assistance" saw little change in its already low centrality over the sample.

Centrality measures an industry's importance as part of the input-output network, not necessarily its importance as measured by share of GDP. While GDP counts only the amount of goods and services that go to final uses, such as consumption or investment (called value added), input-output flows only involve intermediate inputs that are

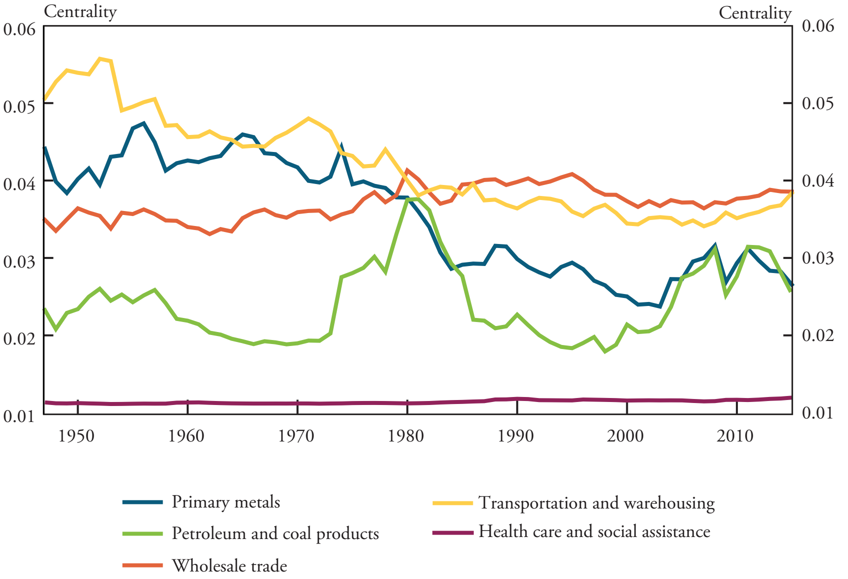
Chart 4

Changing Centrality of Select Industries

Panel A: Select Industries that Increased in Centrality



Panel B: Select Industries that Did Not Increase in Centrality



Sources: Bureau of Economic Analysis and authors' calculations.

excluded from GDP. Therefore, industries that are large providers of intermediate inputs but not final products can have high centrality and low value added, whereas industries that provide final products and relatively few inputs into other industries' production can have low centrality but high value added.

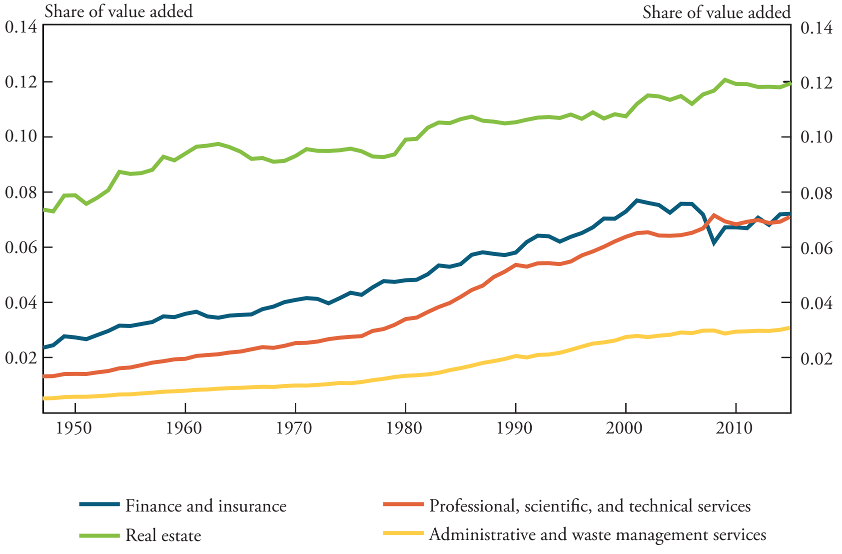
To assess whether these two measures of importance—centrality and share of GDP—are aligned, Panels A and B of Chart 5 plot the share in value added for the select industries originally plotted in Chart 4. Comparing these charts shows that industries with high centrality do not necessarily also have high value added. For example, "primary metals" has a relatively high centrality, because it is an important source of intermediate inputs into many other industries. However, its share of the total value added in the economy is relatively low. In contrast, "real estate" has a moderately high centrality score throughout the sample period but has an extremely high share of value added. The "health care and social assistance" industry grew remarkably as a share of value added, reflecting its growing importance in consumption; however, this growth as a final product was not matched with an increase in centrality, as the industry has remained relatively unimportant within the input-output network. Across all industries and all years, the correlation between an industry's value added and its centrality is 0.41, a moderate level that suggests a not-very-strong link between the two measures. These results highlight that industries that are important from an input-output network perspective may not necessarily be important from a value added perspective. Conversely, just because an industry is important from a GDP perspective does not mean that it has a significant role in the input-output network.

Further analysis of what drives the centrality of industries in the network suggests that highly central industries tend not to be clustered within the network. For each link in the network, we can examine the correlation between the two industries' centrality scores.[7] If high-centrality industries tend to be connected to one another and low-centrality industries tend to be connected to one another, this correlation would tend to be positive and near one. One way to visualize this correlation is as a network structure with a cluster of several highly central industries only connected among themselves and a more diffuse grouping of less central industries that likewise are only connected among themselves.

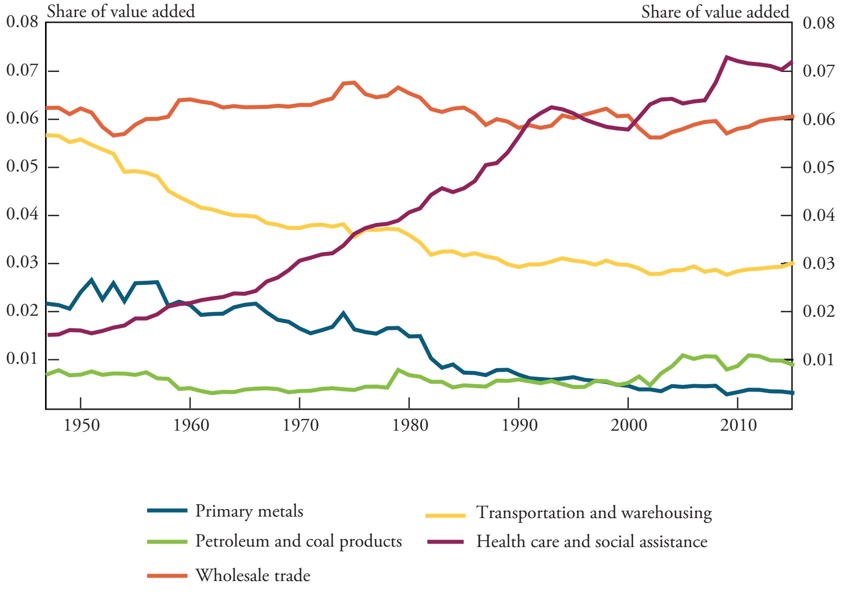
Chart 5

Changing Value Added of Select Industries

Panel A: Select Industries that Increased in Centrality



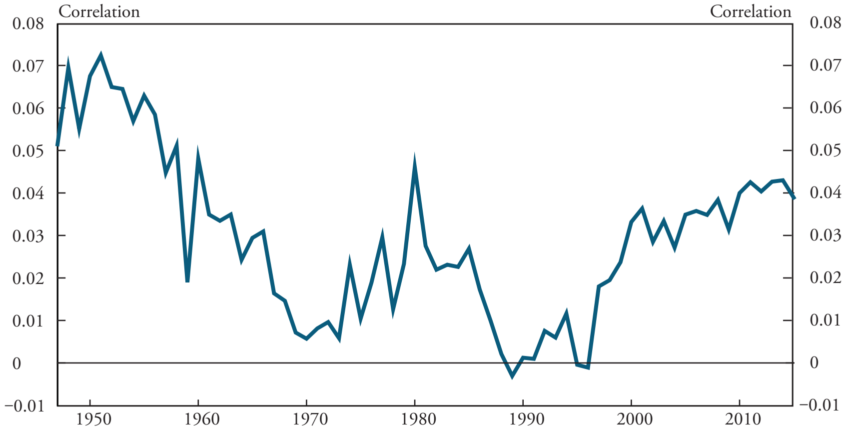
Panel B: Select Industries that Did Not Increase in Centrality



Sources: Bureau of Economic Analysis and authors' calculations.

Chart 6

Correlation between the Centrality of Linked Industries



Sources: Bureau of Economic Analysis and authors' calculations.

On the other hand, if each highly central industry were only indirectly connected to one another and only directly connected to less central industries—in a network structure akin to several separate hub-and-spoke systems—this correlation would be negative. Chart 6 plots this correlation over time for the U.S. economy. While the correlation shows some variation, it is consistently positive and close to zero. This result indicates that connections are distributed quite evenly between high- and low-centrality industries. In other words, highly central industries tend to be connected to both each other and to low-centrality industries.

V. Conclusion

The input-output network structure of the U.S. economy has undergone several changes from 1947 to 2015. The level of interconnection between industries, as measured by network density, rose at the beginning of the sample and declined toward the end, largely due to specific industries that gained or lost connections. But changes in data collection at two points in the sample also lowered overall network density by introducing new industries that were, on average, less connected than their previous, aggregated forms.

In addition, the centrality of industries has varied over time, with certain industries, often services-based, increasing in centrality over our sample. Our analysis of centrality shows that the most central industries tend to be spread across the network rather than clustered and that this feature has held over time.

The changing network may have implications for interpreting movements in the macroeconomy. However, an important caveat in deriving policy implications from our analysis is that we have only illustrated how interconnectivity and centrality have changed over time; stronger policy conclusions might depend on several issues beyond the scope of our analysis such as the quantitative importance of the network in generating fluctuations, how economic inefficiencies interact within the network, and how easily firms can substitute inputs for one another. Nonetheless, establishing how the input-output network of the U.S. economy changed over time is an important step in addressing these and similar issues.

Endnotes

[1]As a caveat, even if the network structure does change over time, that change may not be relevant for some economic outcomes. For example, Foerster and others show that changes in the input-output structure do not help explain changes in how important industry-level shocks are to overall industrial production.

[2]These examples follow and extend those used by Carvalho.

[3]In this process, we combine the make and use tables before redefinitions to capture flows between industries. The make table shows the production of commodities by industries, and the use table shows the uses of commodities by intermediate and final users.

[4]In an online-only supplement, we provide these graphs for every year of our sample, 1947–2015.

[5]In these graphs and the subsequent analysis on network density, we assume a link exists from industry *i* to industry *j* if industry *i* supplies at least 1 percent of industry *j*'s input bundle.

[6]While several different measures exist, we use the Katz-Bonacich measure of centrality in this paper. This measure implies the centrality of an industry *j* is given by $c_j = \lambda \Sigma_i W_{i,j} c_i + \eta$, where W_{ij} denotes the link from industry *i* to industry *j*, λ>0 is an attenuation factor, and η is a baseline centrality. Following Carvalho, we set λ=0.5 and η=(1-λ)/N, where N=46 is the number of industries.

[7]Specifically, if c_i and c_j denote the centrality of industries *i* and *j*, respectively, we are computing $corr(c_i, c_j)$ for all pairs of industries for which a link exists.

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