The multilayer structure of the financial system

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Abstract

We introduce a multilayer network as a framework for analyzing the emergence and propagation of risk within the financial system. The layers of the network encompass assets, funding, and collateral. Various entities in the financial system occupy these layers. For example, asset managers occupy the asset layer, and central counterparties occupy the collateral layer. Some entities span layers. For example, leveraged managers such as hedge funds span the asset and funding layers. Banks are notable in spanning all three layers, and thus are central to the spreading of risks. We show that a multilayer network structure presents risk characteristics that differ from those of a single layer network, and can generate more extensive vulnerabilities and more abrupt, multi-stage cascades than appear in a single-layer network.

Keywords: Financial system, Multilayer network, Financial stability
JEL: G01, G02, C02

1. Introduction

The financial system is built upon a complex set of interdependencies spanning funding flows, counterparty and credit relationships, and asset price dynamics, all passing through many distinct and heterogeneous institutions. A stress to one part of the system can spread to others, often threatening the

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stability of the entire financial system. What is more, a stress in one function of the system can spread to affect another function. Stresses in funding might affect assets, and stresses in assets might in turn affect collateral and counterparty risk. Stresses in a Bank/Dealer might spread to affect a hedge fund, and stresses in the hedge fund might affect a central counterparty. For example, a Bank/Dealer facing a shortfall in funding might reduce the lending it provides to hedge funds, and to control their risk the hedge funds might respond by liquidating asset positions, with the resulting drop in prices compromising collateral values. Thus the flow of funding from one node to another affects the asset flows. Similarly, if asset prices suddenly drop, collateral flows will be affected, which in turn will then change available funding.

The key issue that makes the analysis of systemic risk difficult in a network setting is not so much the size or complexity of the network, but these varied characteristics and functions of the nodes, and the many facets of the flows from one node to another. What is more, the flows do not simply move from one institution to another; the institutions take the funding, credit, and asset flows and transform them in various ways. There are maturity transformations, the standard banking function of taking in short term deposits and making longer-maturity loans; credit transformations through the repackaging of debt instruments as structured products, for example where assets such as mortgages are broken up into tranches of varying credit risk; liquidity transformations, where less liquid assets are restructured and supported by market-making, such as ETFs which provide intra-day liquidity to less liquid assets; and risk transformations, where the return distribution of assets is changed, such as by issuing options with an asset as the underlying. Any analysis of systemic risk that does not account for this multifaceted characteristic of the financial network will fail to track the dynamics of the process.

Network science has been found to provide valuable insights in different scopes in the financial system: descriptions of systemic structure, analysis and evaluation of the penetration or contagion effects (Summer, 2013; Lillo, 2010; Kenett et al., 2012a,c; Cont, 2013; Glasserman and Young, 2015; Garas et al., 2010); studies that assess the impact of the insolvency of one or a particular group of actors in the system, depending on its relevance and connectivity within the structure (Jackson, 2010; Battiston et al., 2012); studies that allow to evaluate the impact of liquidity problems at specific times and initiated in different nodes of the system (Haldane and May, 2011;

Haldane et al., 2009; Cont et al., 2010; Amini et al., 2012; Kenett et al., 2010, 2012b); the structure of interbank exposure networks (Boss et al., 2004, 2006; Elsinger, 2009; Hüser, 2015). Considering the problem of contagion, Allen and Gale (1998) study how shocks can spread in the banking system when it is structured in the from of a network; Drehmann and Tarashev (2013) develop a measure that captures the importance of an institution, in term of its systemic relevance, in the propagation of a shock in the banking system; Acemoglu et al. (2013c,b,a) develop a model of a financial network through its liability structure (interbank loans) and conclude that complete networks guarantee eficiency and stability, but that when negative shocks are larger than a certain threshold, the effects of contagion prevail, leading to systemic instability.

The manifest characteristic of this wide range of inquiry is that the financial system is depicted as a single network, with nodes operating in a homogenous fashion and with the links between the nodes treating one type of flow. Of course, in fact the financial system has many types of agents, and the flows that are relevant differ from one agent to another, and even differ within the same agent from one activity to another. Thus, the financial system operates on a number of layers, and cannot be represented as a single-layer network.

In this paper we present a multilayer network depiction of the financial system. Very little research has been focused on the multilayer network properties of the financial system, and these have been focused at particular aspects of the financial system, and not the system as a whole (see Bargigli et al. (2015); Bravo-Benitez et al. (2014)). The network also has heterogeneous nodes or agents that in some cases sit on one of the network layers, and in other cases span layers. Indeed, the types of agents can be defined by the nodes in which they operated, whether they are core or peripheral to the nodes, and whether they are providers, users or intermediaries for the flows in the various layers on which they operate. The multilayer network has implications for systemic risk that are qualitatively different than those for a single layer network. Perhaps not unexpectedly, the mode of propagation of risk, the path a shock takes, and the value of integration versus segregation of the functions of various agents or nodes all have a different and richer nature as we move to a multilayer view of the financial system.

2. Mapping the structure of the financial system

The multilayer network encompassing the financial system has specific agents operating on each layer, and some types of agents spanning between layers. In particular, we present the financial system as a three-layer network, with an asset, funding, and collateral layer. In this section we will describe the nature of the agents in each of the layers within the broad structure of a map of the key agents and their interactions. For each layer of the network we will highlight the components of this map that are relevant to that layer. The asset and collateral layer both interact with the funding layer and so we will describe that layer first.

2.1. Funding layer

Recently, Aguiar et al. (2014) introduced the first mapping of the flow of funding in the financial system. The dynamics of the financial system and the undercurrents of its vulnerabilities rest on the flow of funding, which are typically represented as a network with banks and financial entities as the nodes and the funding links as the edges. Aguilar *et al.* extend this focus to treat the funding operations within the nodes: the intermediation and transformation functions provided by the Bank/Dealers (BD) and the decision heuristics of the funding providers and users. This adds a critical level of detail about potential funding risks. We use this map as the schematic for the funding layer of the multilayer network.

The key aspects of this funding map are highlighted within the broader map in Figure 1. It shows how funding and securities move among key elements of the bank: the prime broker, which interacts with customers such as hedge funds; the trading desk, which provides market-making for customers and hedging for internal risks; the derivatives desk; and the corporate treasury of the Bank/Dealer, which provides the equity and debt issuance. At the center, where all roads seem to lead, is the Bank/Dealers financing operation. This is where securities purchased or received from counterparties as collateral are rehypothecated as collateral to obtain funding through the repurchase (repo) market, and where securities are obtained through reverse repo and securities lending transactions to fulfill short requirements, provide financing to clients, or for other internal Bank/Dealer needs (e.g., liquidity investment).

Furthermore, the funding map provides more detail about the nature of the Bank/Dealers relationships with its customers with respect to sources

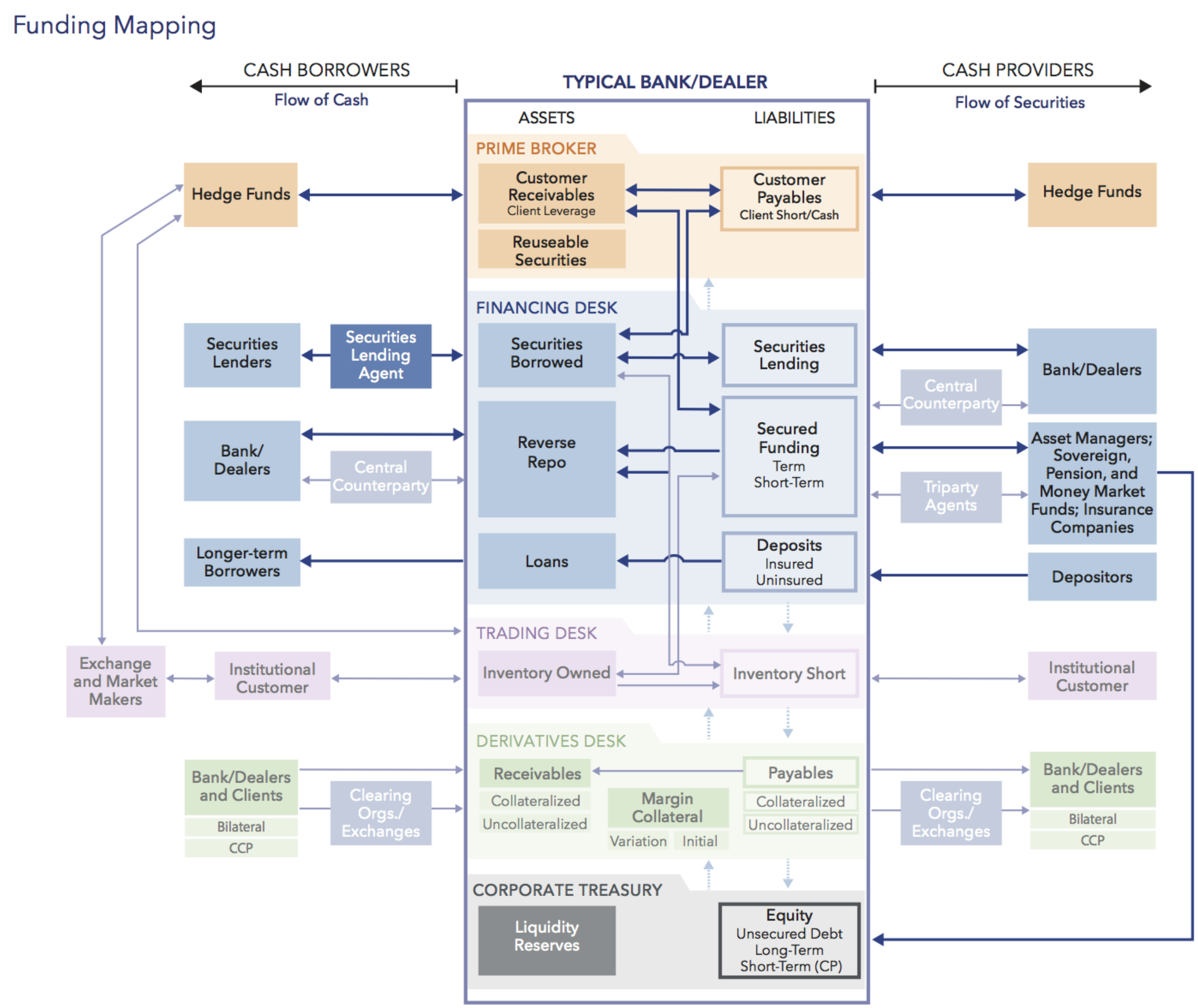

Figure 1: The funding map of a typical Bank/Dealer and related entities. This provides detail into the internal workings of a Bank/Dealer as the intermediary for passing funding from the cash providers to the cash users. It highlights the key components of the entities and the Bank/Dealer functions that are involved in funding. At the center, where all roads seem to lead, is the Bank/Dealers Financing Operation. This is where funding is obtained, largely through the repurchase (repo)market, and where securities are obtained through reverse repo and securities lending transactions to fulfill short requirements. See also 1

and uses of funding and securities. The map shows the Bank/Dealer operating within the interbank market, the standard relationship in most network approaches to the financial system, and in a broader financial landscape that includes money market funds, pension funds, hedge funds, and others. The Bank/Dealer obtains securities to lend to clients and to cover exposures in its own trading operations through many of these same parties. The Bank/Dealer is also connected to other entities in its role of providing funding and securities, often to the same types of entities that provide its funding and securities.

The funding map provides a detailed view of the business activities perfromed by financial market participants with a directional display of the exchange of cash or securities, a representation of the durability of funding sources, and the illumination of the stress triggers and amplifiers of funding-related risks between participants, with the objective of understanding the funding risks within the financial system as a whole and the potential for contagion given the interrelationship of participants.

2.2. Collateral layer

All flows of secured funding are met by collateral flows in the opposite direction. Thus, as noted in Aguiar et al. (2014), the funding map is implicitly a collateral map as well. The two-way street of secured funding and collateral is depicted on Figure 1 with connecting lines that have arrows on both ends. A network depicting funding flows thus implicitly reveals a network of collateral flows. However, collateral can also be presented as its own network, depicted by the collateral arrangements, ranging from bilateral, to tri-party, to centrally cleared; by the transformation of collateral though upgrades and re-use; and by the risk management of collateral based on haircuts and quality.

Aguiar et al. (preprint) have performed a detailed mapping of the flow of collateral in the financial system. In a similar fashion to the funding map, they charted out the collateral map, focusing on the key entities involved in collateral transactions, and the dynamics of its flow, and provide insight into how collateral can contribute to a financial crisis by creating vulnerability that accelerates and propagates from one institution to another, ultimately affecting the financial stability. The collateral map shows the path of collateral to its end points, differentiating the paths for bilateral, tri-party, and CCPs. Each of these paths facilitates different transformations of collateral, such as reuse, upgrades, and credit transformations.

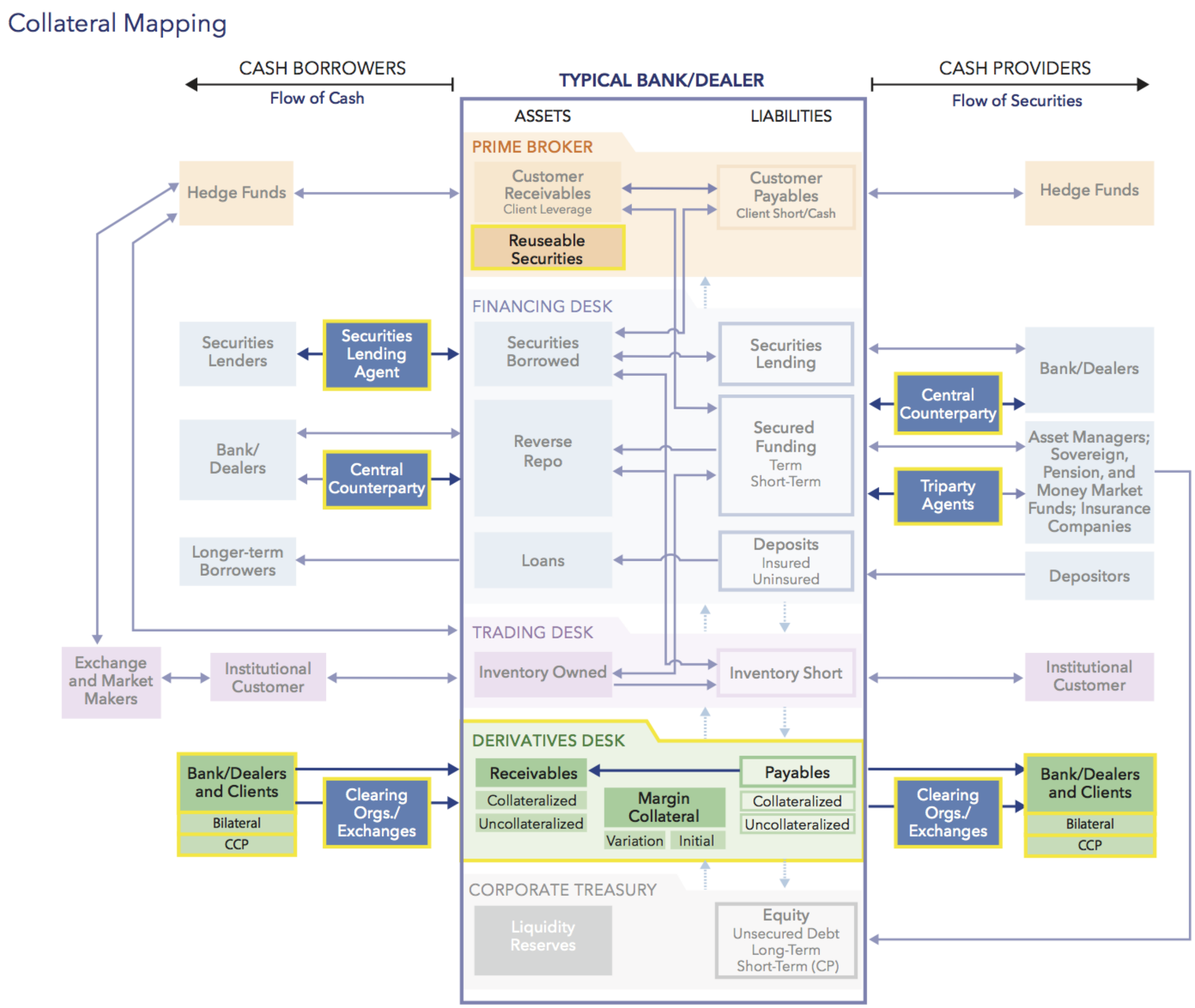

Figure 2: Collateral map for a typical Bank/Dealer and related entities. In a similar way to Figure 1,, here we highlight in the general schematic the typical entities involved in the fl w of collateral, the different flow and use mechanisms involved in the transfer of collateral. Furthermore, there are different roles played by the entities involved in the transfer of collateral.

Figure 2 highlights the key components that are part of this collateral map, which depicts the pathway of collateral across the various agents. This figure contains more detail than other network analyses in at least two respects. First, it gives detail into the internal workings of a Bank/Dealer and its central roles in intermediating the flow of collateral. It shows that collateral comes into the Bank/Dealer through a number of channels, and it is then dispatched through a number of routes: bilateral, tri-party, and CCP. The Prime Broker is the conduit of collateral from the hedge funds; the Financing Desk for securities lending and repo; and the Derivatives Desk for futures, forwards, swaps, options, and related activities. The Bank/Dealers Financing Operation is the engine for key collateral transformations. It is through the Financing Desk that collateral is re-used and where collateral upgrades are managed. Underpinning all of this activity is the collateral management function at the Bank/Dealer, which dictates the level of collateral and the quality of collateral that can be used for Securities Financing Transactions and Derivatives obligations. Second, a key aspect of the collateral map is the pipelines for collateral flows. Collateral can be passed directly to the funding agent as a bilateral flow, can be held by a tri-party agent, where all counterparties have their collateral pooled but where that pooling remains distinct for each borrower; or can be passed to a CCP, where the collateral could pass through to other CCP members.

2.3. Asset layer

The third layer is that of the asset network. Although, in light of the funding- and leverage-induced failures of the 2008 crisis, much of the recent network literature in finance focuses on the funding network in one from or another, the asset network is what is more commonly thought of as the embodiment of the financial system and has historically been the topic of network representations. Figure 3 presents a canonical asset network. The asset network includes the flows of assets and cash between asset managers and the security markets. The network thus includes mutual funds, hedge funds, the trading and investment arms of insurance companies and pension funds as peripheral nodes, and the exchanges and market makers as nodes in the core. In most cases the asset managers do not span to the funding layer, but as is clear from the funding map of Figure 1, leveraged investors that use funding and securities lenders that provide funding will be nodes in the funding layer as well.

Figure 3 presents the asset map in the context of the funding map and collateral map. The central components of the asset map are the market makers. There are exchanges for a range of asset types, most notably equities. For other asset types, most notably the rates and credit instruments, the principle market making activity rests with the trading desks of the broker dealers within the bank dealers. Some of these markets are moving toward electronic trading, for example the swap execution facility. However, the mode of trade communication and clearing is not the focus of the map; rather it is the channels through which the trading occurs. The mode of execution may differ in periods of day-to-day levels of trading versus trading during periods or market dislocation, with voice trading becoming more dominant in the latter case.

3. The financial system as a multilayer network

Multilayer networks (Boccaletti et al., 2014; De Domenico et al., 2014) explicitly incorporate multiple channels of connectivity and constitute the natural environment to describe systems interconnected through different categories of connections. Each channel is represented by a layer and the same node or entity may have different kinds of interactions with different set of neighbors in each layer. For instance, in social networks, one can consider several types of different actors relationships: friendship, vicinity, kinship, membership of the same cultural society, partnership or coworkership, etc. Such a change of paradigm, which has been termed in disparate ways (multiplex networks, networks of networks, interdependent networks, hypergraphs, and many others), has already led to a series of relevant and unexpected results (though up to this point not explicitly to chart the structure of the financial system). One of the first examples of multilayer networks that has been thoroughly investigated and modeled, and sparked this strain of research, is the 2003 Italian blackout. On September 28, 2003, Italy experienced a country-wide blackout that propagated through the vulnerabilities of a multilayer network. Electric power moved as edges emanating from nodes of power stations. Italy had a second network for communications that among other things was used to send the controls for the operation of the power network. On that day, one node in the power network failed. That failure of that one node started off a cascade which enveloped the countrys entire power system. The one node in the power network spanned to the communication network by disabling a nearby server. One server failure af-

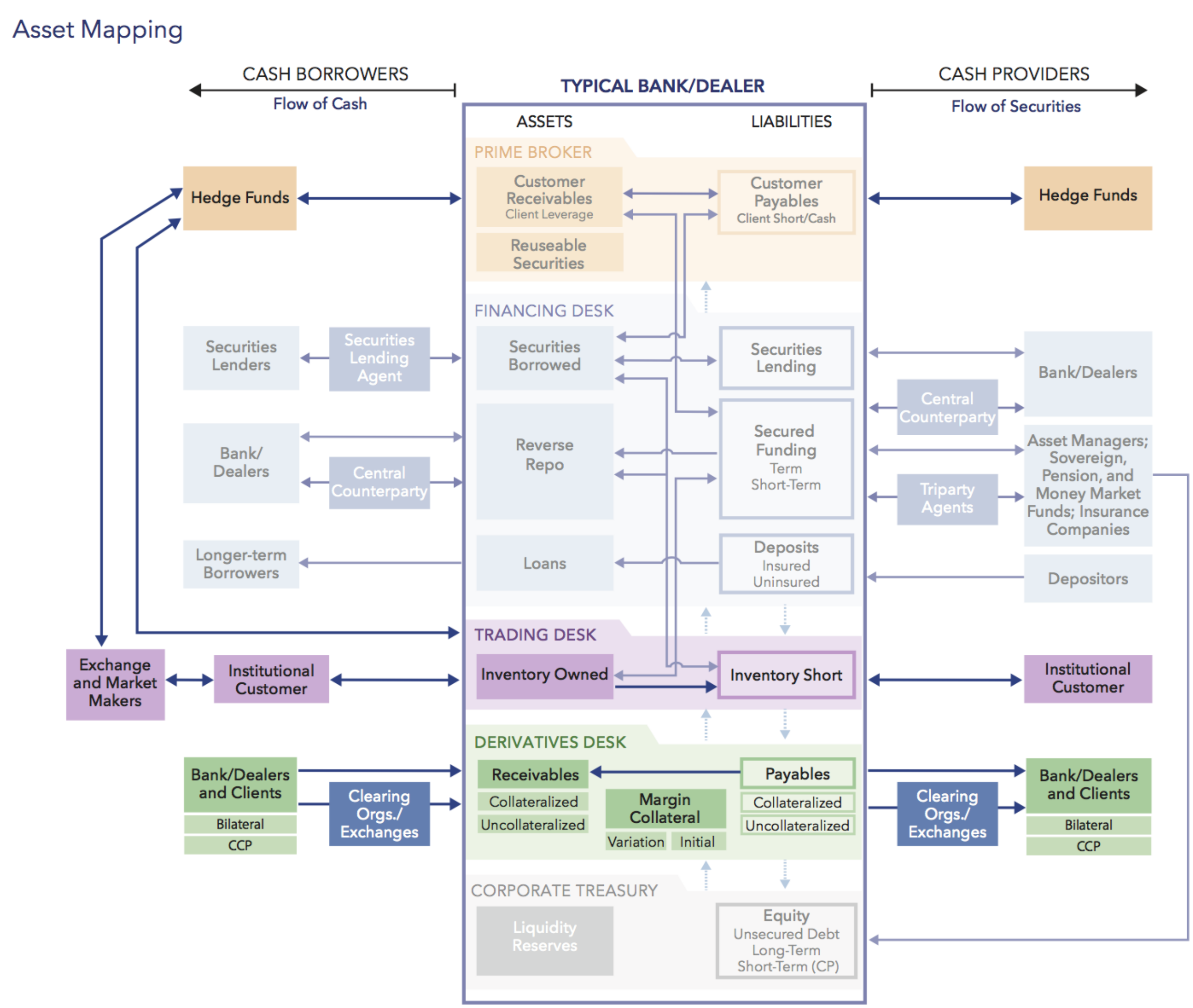

Figure 3: Asset map for a typical Bank/Dealer and related entities. Following on from Figure 1 and Figure 2, here we highlight the typical entities involved in the asset market, most notably the entities that have asset positions and the exchanges and market makers that facilitate the asset flows. Different avenues are used depending on the asset type. Equities mostly use exchanges, credit and rate instruments trade through broker-dealer desks, and swaps and other derivatives through banks either on a bilateral or CCP basis.

fected adjacent servers because they depended on the one server as a part of their communication cluster. The power stations that were connected to these servers then shut down due to the loss of their controllers, which in turn affected the servers adjacent to that node. The failure propagated in hop scotch fashion from one power node on the power layer to a node in the communication layer, from that one communication network node to other nodes on the communication layer, and then back to the power node through these servers. The result then propagated to other networks ranging from railways, to healthcare, to the financial system, and to other communication networks distinct from the communication network with the close proximity to the power grid (Rosato et al., 2008; Buldyrev et al., 2010). The vulnerabilities came both because the communication and power networks were highly interdependent the servers depended on power, and the power depended on the control of the servers – and also because the networks were similar in topology and geography, with communication nodes closely matching up with power nodes.

In Figure 4 we present a schematic representation of this multilayer structure. As some financial entities participate in more than one layer, this results in the dependency and connectivity between the different layers. One main source for this is the Bank/Dealer, which participates in all three layers, with the mode of participation varying from one of its sub-units to another.

The multilayer network formalism presented Figure 4 is made up of three layers: the Asset Layer, Funding Layer, and Collateral Layer. The three layers are of a core-periphery topology. The core nodes are the exchanges and market makers for the asset layer; the Bank/Dealer intermediaries for the funding layer; and the CCPs and tri- party repo agents for the collateral layer. For the assets, the peripheral nodes are those that engage in buying and selling of assets, such as hedge funds and asset managers. For the Funding Layer, the peripheral nodes are the suppliers and users of funding that engage through the Bank/Dealer intermediary. We can also differentiate the nodes based on the directions of flows or linkages in the different layers, as suppliers, user, and intermediaries. For funding, the supplier is the cash provider, the user is the hedge fund. For assets, the peripheral nodes act as both suppliers and users, where these function might be defined either in terms of being sellers and buyers, or in terms of being those that provide liquidity and those that demand it. For collateral, the supplier is the one that is receiving the funding, the user is the one who receives the collateral. In some cases the peripheral nodes might interact directly, such as in the case of bilateral swap

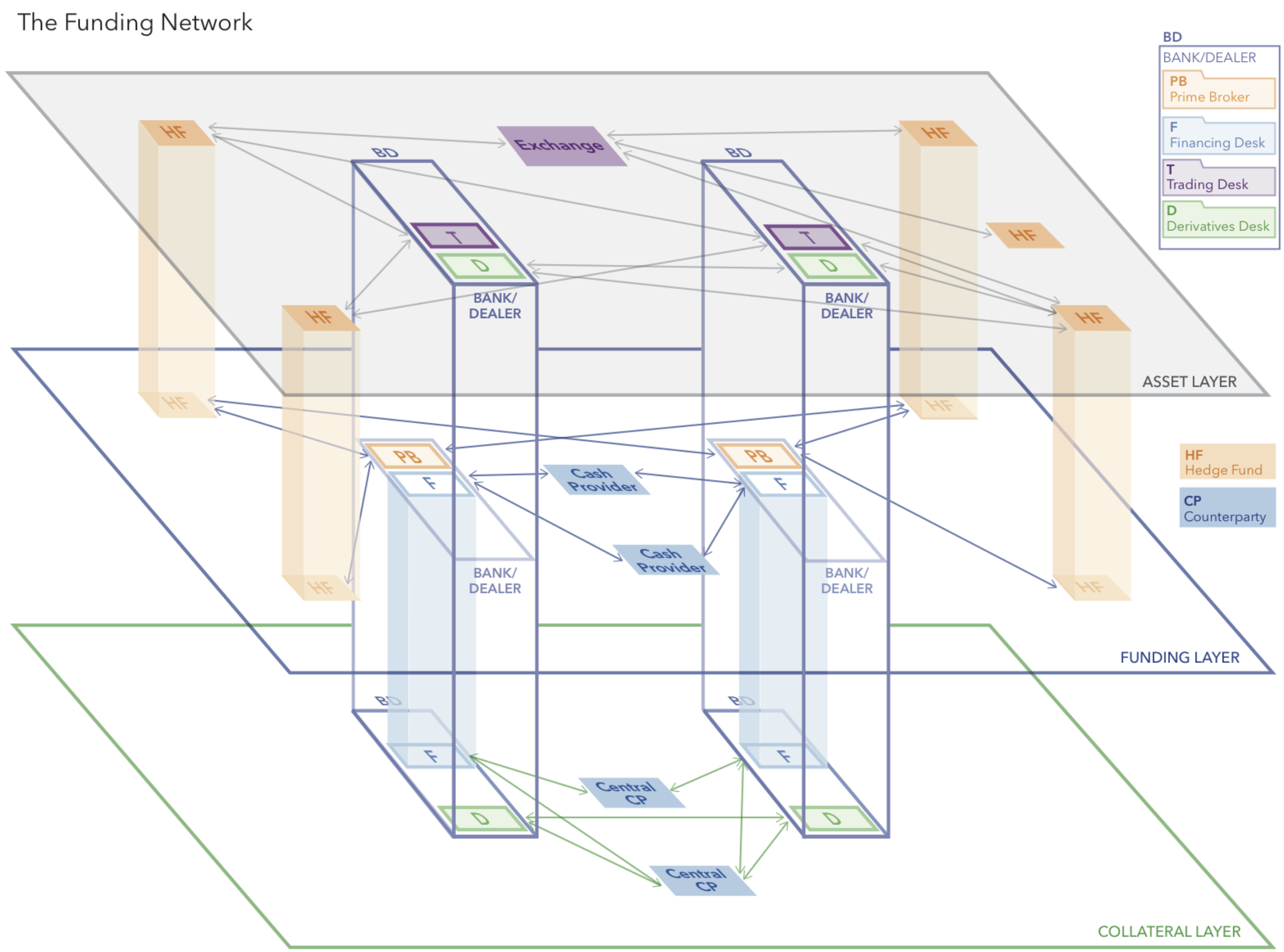

Figure 4: A multi-layer network view of the financial focused on the Bank/Dealers and related entities. This multilayer view restates the components shown in the funding, collateral, and asset maps of Figures 1, 2, and 3, with the various entitles represented as nodes, and with examples between them. Some financial entities participate in more than one layer, resulting in the dependency and connectivity between the different layers. Particularly notable are the Bank/Dealers, which participate in all three layers, due to activities of its various sub-units.

transactions.

The main agents of each of the various layers include, with notation for whether they are suppliers and/or users, and whether they are core or periphery within the respective network are detailed in Table 1.

As is evident from Figure 4 and Table 1, some financial entities span across layers with the Bank/Dealers being unique in spanning all three layers – while some only operate in an individual layer. The role of an institution that does span layers may differ from one layer to another. For example, a hedge fund is defined as being a buyer and seller of assets and a user of funding. The nature of the spanning, the position in the core-peripheral topology, and the function of the node can provide a blueprint to define new categories into which financial institutions will fall, based on the level of their activity in the different layers. That is, we can define financial institutions by type based on which layer they operate, whether they are core or periphery, and whether they are providers or users. The degree to which an institution that acts as a core node also spans layers gives a measure of its importance from a systemic risk standpoint. As we will see below, these characteristics can lead to more fragility than is exhibited by core nodes within a one-layer network.

Although it is only suggestively illustrated in Figure 4, the number of central and periphery nodes vary in a notable way from one layer to the next. While all portraying core-periphery topologies, the number of nodes vary in order of magnitude, roughly speaking, from one layer to the next. This is shown in Table 2, where we outline the core and periphery entities in each layer, and their representative number within the financial system. In terms of core nodes, there are hundreds of exchanges and market making institutions, perhaps a few dozen intermediaries for funding, and only a handful of central counterparties of note. In terms of the peripheral nodes, there are tens of thousands of institutional investment firms (ignoring retail investors), with only a fraction of these involved in funding. And the peripheral institutions for collateral are those that are involved in either bilaterally and through a central counterparty, and this is broadly restricted to a subset of the Bank/Dealers. An important question which will remain beyond the scope of this paper is whether this order of magnitude difference in the number of nodes contributes to the nature or severity of the propagation of shocks in and between the different layers, suggests specific points of vulnerability, and thus is an additional key feature of the financial system that can be manifest through the multilayer network. For example, is there a higher

Table 1: The agents that occupy the various layers of the network, along with their node type and function within that layer, and their primary federal regulator.

		Node		Function			Primary regulator
Layer	Agent	Core	Peripheral	Supplier	Intermediary	User	
Asset	Hedge Funds		x	x		x	SEC, CFTC
	Asset Manager		x	x		x	SEC
	Bank/Dealer Market Makers	x			x		OCC, FED, SEC
	Bank/Dealer Derivatives	x			x		OCC, SEC
	Exchanges and Non-bank market Makers	x			x		SEC, CFTS, SRO
Funding	Hedge Funds		x			x	SEC, CFTC
	Cash Providers		x	x			NA
	Bank/Dealer Finance Desk	x			x		OCC, FED
	Bank/Dealer Prime Brokerage	x			x		SEC
Collateral	Cash Providers (pension funds, insurance companies		x	x			Department of Labor, State insurance departments, FIO
	Derivatives		x	x		x	CFTC
	Bank/Dealer Financial Desk	x		x		x	OCC, FED
	Central Counterparties (CCPs)	x			x		SEC, CFTC, FED
	Tri-party Repo Agents	x			x		FED

Table 2: Summary of key entities in the different layers, their role (core or periphery) and their representative number.

	Assets	
	Type	**Number**
Central	Market maker	~ 100
	Exchange	
Peripheral	Hedge Funds	$\sim 10,000$
	Asset Managers	
	Funding	
	Type	**Number**
Central	Funding Agent	~ 10
Peripheral	Hedge Funds	~ 1000
	MMF	
	Collateral	
	Type	**Number**
Central	CCP	~ 1
Peripheral	Bank/Dealer	~ 10
	FCM	

risk of propagation when a node is disrupted or a shock occurs in a more sparsely populated layer.

Characterizing the financial system as a multilayer network provides the opportunity to rethink and redefine its structural properties, which are constantly evolving and adapting, and relationships that might be come to the fore during a financial crisis. In the current financial system, financial institutions can be involved in activities that do not directly fall under the specific title or definition of the given institution. As such, an important issue that arises is how to apply regulations, which often addresses specific financial institutions. Viewing the institutions within the context of the multi-layer network can assist policy makers in monitoring cross-layer institutions, and provide the means of calibrating regulation policies for the diff t categories. Furthermore, it will provide the means for tracking how fi institutions change their nature, in terms of their activity in the different layers, and monitoring how a financial entity changes its activity in a given layer. Understanding how it spans across the different layers will provide a new monitoring framework to ensure financial stability. The multilayer formalism provides new insights into the structure of the financial system, and its function through the dynamics of processes in and between the layers.

When first presented, the distinction between what occurs in a multilayer versus single-layer network was a surprising result and spurred an active subfield in network science. Intuitively, the links between layers give an avenue for propagation that makes it less likely that a shock will remain contained, creating a branching channel akin to how an elevator shaft can allow a fire to spread from floor to floor. Utilizing the knowledge on the spread of damage in a multilayer interdependent network, we can identify three critical stages, as highlighted schematically in Figure 5. This phenomenon has been observed for several different multilayer network systems, and can thus be predicted also for the financial system. Such knowledge provides new insights into cascade process in the financial system, and highlight the different stages. Making use of such knowledge provides new opportunities for policy and decision makers to decrease the extent of the effect of the damage once it begins, and ultimately contain it and introduce strategies that will push the system into a recovery mode (see for example Majdandzic et al. (2014)). The multilayer interdependent network framework describes the propagation of damage in three distinct stages: 1) a fast, strong collapse of the system; 2) a slow, long period in which the damage propagates slowly throughout the system, in an analogous fashion to cracking ice (see Zhou et al. (2014)); and 3) a final fast strong collapse of the system. This dynamical process results from a balance that exists between different states of the system. These two states can be defined as damage amplification (two cascading stages highlighted in Figure 5) and damage saturation (plateau stage in Figure 5). In the damage amplification stage, any damage in the system leads to yet more extensive or severe damage. For example, removal of one node will lead to a failure of ten nodes, which will lead to a failure of one hundred nodes, and so forth. In the damage saturation stage, the damage is constant, and a damage of one node will lead to a damage of one node, and so forth.

Understanding the effect of financial crises and how they propagate through out the entire system is critical in order to maintain and ensure financial stability. While it is important to understand the vulnerability of each layer by itself, when considering the system as a multilayer network, new threats and vulnerabilities are discovered. Thus, applying the lessons learned from this framework to the financial system will provide new insights and tools in order to maintain its stability and functionality. Multilayer networks encode significantly more information than their single layers taken in isolation, since they include correlations between the role of the nodes in different layers

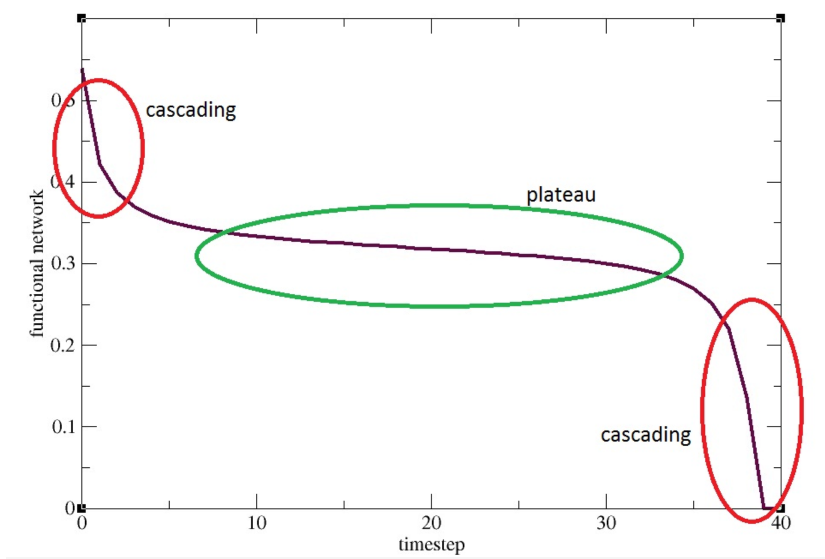

Figure 5: Stages of the propagation of damage across the multilayer networks. The multilayer interdependent network framework describes the propagation of damage in three distinct stages: 1) a fast, strong collapse of the system; 2) a slow, long period in which the damage propagates slowly throughout the system, in an analogous fashion to cracking ice; and 3) a final fast strong collapse of the system.

and between statistical properties of the single layers. As discussed above, multilayer networks have been found to be significantly more fragile in comparison to the case of single isolated networks. This can be attributed to the connectivity and dependence between the different layers, or networks, in the system. Recently Reis et al. (2014) and Boccaletti et al. (2014) have distinguished between different types of similarities of the network layers, which result in inter-layer connectivity and dependence. These include interlayer degree correlations (indicates if high (low) degree nodes in layer A will be high (low) degree nodes in layer B); overlap of connectivity patterns in two or more layers of the system (the overlap of the links can be quantified by the global or local overlap between two layers, or by the multidegrees of the nodes that determine the specific overlapping pattern); node pairwise multiplexity (correlation of two, or more, nodes connectivity patterns in the case where not all nodes are active in all the layers of the system); layer pairwise multiplexity (correlation of two, or more, layers in terms of connectivity patterns, when not all nodes are active in all layers); full dependence; and partial dependence. Whereas random links between interdependent networks represent dangerous liaisons, enhancing the fragility of the entire system, the trustworthy links between the networks are not random, but correlated in a specific way. First, the links between the layers must be such that the highly connected nodes, or hubs, of the single layers are also the nodes with more interlinks. And second, there must be multilayer assortativity. This means that for two layers, A and B, the hubs in layer A (layer B) are more likely to be linked with the nodes in layer B (layer A) that are connected with other hubs in layer B (layer A) (Bianconi, 2014). However, current studies have shown that interbank networks have low assortativity (Bargigli et al., 2015), which raises the question about the stability of the interbank system. Thus, we aim to study the level of overlap and correlation between the structure and function of the different layers. This knowledge, together with the insights learned from the previous two propositions, will provide the full picture of the structure, function, and resilience of the financial system. These results provide critical quantitative information to address this important question of integration versus segregation in the financial system (addressing such debates as the Glass-Steagall regulation and too concentrated to fail). We can replicate these results using real network topologies, as outlined in the previous section, and simulate different scenarios of dependency level between the different layers. One such approach to achieve this goal is to use an Agent Based Model (ABM) approach, as recently introduced by Bookstaber et al.

(2014). Combining the ABM with the multilayer framework would provide the means to stress test different scenarios for varying levels of dependency between the layers of the financial system.

Finally, the multilayer network has important implications for the issue of systemically important financial institutions. To the size of an institution, and even its centrality in terms of any one financial function we can add the importance of the institution for spanning the various layers. That is, if an institution can express the disruption in one layer through another layer, it is moving a local (layer-specific) disruption in to a systemic (multilayer) one.

4. Applications, challenges and data gaps

The specific application and implications of these properties to the financial system are beyond the scope of this paper; our intent is to extend on the mapping of the financial system and place it more explicitly in the multilayer network framework. The previous section highlights critical aspects of the financial system, when investigated as a multilayer network:

1.) Understanding the financial system as a multilayer network results in the need of modifying contagion models for the financial system. These new models must take into consideration the spread of the shocks between the layers, and how the connectedness and dependence between the layers lead to the amplification of the shock.

2.) Rethinking how financial institutions are defined, according to their activity in the different layers. This will require rethinking regulation and monitoring policies, and provide new definitions into systemically important financial institutions.

3.) Provide quantitative evidence into the effect of integration versus segregation in the financial system. This is becoming increasingly important considering how financial institutions, such as banks, are branching out into new financial activities.

4.) Develop new models to characterize the resilience and vulnerability of the financial system. This should lead to the development of a new class of stress tests, and ultimately to a class of intervention strategies.

5.) The multilayer network formalism can lead to new understandings on the evolution of the financial system, and on link formation. When links are formed in one layer, this can lead to link formation in related networks, as well as link deletion.

These challenges require both theoretical, numerical, and empirical efforts. The existing theoretical framework for multilayer networks needs to be adapted for the case of the financial system, such as the definition of the dependence between the layers. The models of shock propagation and contagion for financial networks needs to be revised to address the multilayerness of the system (see for example Kenett and Havlin (2015)). Finally, to calibrate the models and provide quantitative insights into the challenges mentioned above, there is a need to tie in several different counterparty data sources. This requires a significant data collection effort, as the different financial institutions answer to different regulators (see Table 1). Data collection efforts have significantly increased and expanded following the 2008 financial crisis (see for example Baklanova (2015); Balklanova et al. (2015); Johnson (2015)). However, while more aggregated data is being collected, these data collection efforts rarely include counterparty exposure information. Currently, available counterparty datasources, in the context of this framework, include tri-party repo data, swap data, CDS data and bond market dealer counterparty data. However, these provide only partial information, and are far from being sufficient for describing the full structure of the three layers discussed above, nor the connections or dependencies between the layers. This is a crucial data gap and challenge that needs to be resolved in order to uncover the underlying structure of the financial system and provide full information on sources of systemic risk.

Some initiatives are attempting to address this challenge. One such initiative that is currently being discussed is the Qualifying Financial Contracts (QFC) rule proposed by the Financial Stability Oversight Council (FSOC), which is aimed at closing this gap (FSOC, 2015). A QFC is a securities contract, commodities contract, forward contract, repurchase agreement, swap agreement, or any similar agreement that the FDIC determines by regulation, resolution, or order to be a qualified financial contract; and a covered financial company, which is governed by the rule, is a financial company, other than an insured depository institution. The rule, if passed, would deem certain financial companies as record entities, which would require them to keep electronic records of all QFCs, and provide them to its primary regulator within 24 hours of a request to do so. These filings would include full position data and collateral counterparty data.

The QFC record keeping framework, or other alternatives, would provide a first full description of the interconnectedness in the U.S. financial system. Such information would provide the means to calibrate the model and challenges discussed above, and provide new insights into the stability of the financial system, and how to manage it.

5. Summary and discussion

Financial risks can be described as originating and then propagating through a three-layer system of assets, funding, and collateral. We can consider risks that are layer specific - asset prices and liquidity; funding liquidity and leverage; and the collateral of secured lending as well as the counterparty and credit risk that the collateral seeks to mitigate - but sources of vulnerability are exposed when considering the dependency and connectivity between the different layers that are not manifest when the financial system is modeled as a single layer network, all the more so when it is modeled as a single layer network with homogeneous nodes. As we move from one layer to the next, the risk is transformed, so that a price shock becomes a funding risk as the impact moves down the network to that layer, and similarly as it moves to the collateral layer it is expressed as a counterparty or credit risk. Or, looking at the dynamic as a shock moves up from the collateral layer, if a counterparty risk leads a CCP to have to sell off positions, they then are pushing activity and risk to the asset layer, and they face liquidity risk due to the market impact of their selling. The structural implications of the multi-layer approach include:

1. The definition of an agent or entity is determined by the layers on which it operates.
2. The type of risk is determined by the layer on which the risk occurs.
3. The transmission of risk through the system occurs through those agents or entities that span the respective layers. This is why banks are so critical, because they span all three.

We present a schematic for each of these layers, and for the agents in the financial system that connect them. These schematics can provide a structure for investigating how the effect of the multilayer financial system is capable of withstanding damage or shocks. By understanding the mechanisms of propagation of damage in a multilayer network it will be made possible to present a deeper understanding of the structure, function, and resilience of the financial system.

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