Systemic Risk in the Financial System: Insights from Network Science

Ross A. Hammond[1]

Introduction

The recent financial crisis was characterized by a rapid widespread destabilization of the financial system, with little apparent warning. The crisis has led to fresh attempts to understand the structure of the financial system and what made it vulnerable to instability. One important characteristic of the system is the set of links between actors that form networks of connectivity. The structure of these networks may have enabled disruptions initially affecting only a few financial actors to rapidly spill over into a system-wide crisis.[2]

Network structure may have played a role in the financial crisis in at least three ways:

1. Financial networks may have lacked *robustness*, hampering the ability of the system as a whole to continue functioning even when a few central actors stopped functioning;
2. The pattern of network links may have made the system especially susceptible to *contagion* (both through formal transactional links between institutions, and through informal social networks that connect both customers and individuals within institutions) ;
3. A lack of diversity in financial networks may have impaired their *resilience*, or ability to adapt to a new financial environment by reshaping themselves to recover functionality.

Over the past few decades, a large multidisciplinary scientific literature has developed around the mathematical study of networks—spanning fields as diverse as ecology,[3] physics,[4] sociology,[5] and

[1] Ross A. Hammond is a Fellow in Economic Studies at the Brookings Institution.
[2] Haldane, A.G. Speech delivered at Financial Student Association April 2009; Watts, D. Harvard Business Review June 2009 and; Naylor, M.J. et al. Working Paper, SSRN #1184604 (2008).
[3] May, R.M., Levin, S.A., and Sugihara G. *Nature* 451 (2006); Bellwood, D. et al. *Ecology Letters* 6:281 (2003); Levin, S.A. & Lubchenco J. *Bioscience* 58(1):27-32 (2008); Worm, B. et al. *Science* 314:787-790 (2006).
[4] Callaway, D.S. et al. *Phys. Rev. Lett.* 85 (2000); Newman, M.E.J. *Soc. Industr. App. Mathem. Rev*. 45(2):167-256 (2003).
[5] Watts, D. *Ann. Rev. Sociol.* 30:243 (2004); Centola, D. & Macy, M. *Am. J. Sociol.* 113:3 (2007); Watts, D. *Proc. Natl. Acad. Sci.* 99:9 (2002).

epidemiology.[6] Although relatively new, this field has begun to amass a body of important findings and insights into how networks behave. In this paper, I give an overview of several key findings from network science, addressing in particular the three attributes of networks outlined above (robustness, contagion, and resilience). Where relevant, I will point out general lessons from this literature that may be of interest to regulators and reformers of the financial system—suggesting the types of structures or patterns that might be encouraged or avoided, and the kinds of data that might be useful to understand and monitor network stability.

Network Terminology

A network has two key building blocks: a set of individual elements (called *nodes*), and links between these elements (called *edges*). In the context of the financial system, nodes usually represent individual actors such as firms, banks, and traders, while edges represent interactions between the actors, such as trade, ownership, investment, or lending.[7] Analysis of the pattern of edges and nodes in a network can allow measurement of key properties of the network as a whole, as well as properties of particular nodes and edges individually. One especially important property of a node is its *degree*, defined as the number of edges connected to it.[8] Thus a node of high degree has many connections, while one of low degree has only a few. The distribution of this property across all the nodes in a network—called the *degree distribution*—is an important structural characteristic of the network itself.

Robustness in Networks

The operation of a system driven by interactions across a network of connections between its elements may become disrupted if those connections are severed. *Robustness* is the ability of a network to continue functioning even when nodes or edges are removed. A computer network, such as the internet, is robust if it can overcome the breakdown of some of its computers or information links. A financial network is robust if it can overcome the failure of some of its firms or transaction markets.

A particular focus of robustness research in network science has been on networks whose degree distribution has a right-skewed "heavy tail", such as a "scale-free" or power-law distribution. In these

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[6] Galvani, A.P. & May, R.M. *Nature* 438 (2005).
[7] Schweitzer et al. *Science* 325 (2009).
[8] Newman, (2003).

networks, most nodes have a low degree (few connections), but a few nodes have very high degree (many connections).[9] Such networks are common in many social and natural systems,[10] and there is growing evidence that financial networks may also be of this type.[11]

Scale-free networks have been shown to be very robust against *random* disruptions—because most of the nodes are of low degree, one removed at random is most likely to be only sparsely connected.[12] But scale-free networks are particularly vulnerable to *focused* disruptions affecting high-degree node(s), which are central to the network.[13]

If financial networks are indeed "scale-free", this research has three important implications for systemic risk and financial reform. First, it means that long periods of stability provide no real reassurance about the possibility of catastrophic failure.[14] If firms and other economic actors "fail" at random, most of the time these failures will be small degree nodes and have little impact on the system—which will appear stable. But, sooner or later, a high degree node will fail and will be highly connected enough to jeopardize the whole system. Second, the critical role of high-degree nodes in a scale-free network makes a strong policy argument for *identifying who these actors are* before a crisis strikes. There might be real value in evaluating the concept of "too big to fail" scientifically and systemically using network methods.[15] Third, these results suggest robustness of the network can be substantially enhanced by guarding against failure of high-degree nodes. This might be accomplished by providing a "firebreak",[16] perhaps in the form of a carefully targeted layer of insurance or government backup for those nodes determined to be critical. It might also be accomplished by changing the structure of the network to eliminate high-degree nodes—by forcing them to downsize, restructure, or divide into smaller components, with antitrust law serving as a valuable precedent.[17]

[9] Watts, (2004).
[10] Barabasi, A-L. *Science* 325 (2009).
[11] Schweitzer et al. (2009); Iori (2008); Boss et al. *Quant Finance* 4:677 (2004).
[12] Albert, R., Jeong, H. & Barabasi A.L. *Nature* 406 (2000).
[13] Ibid; Callaway, D.S. et al. *Phys. Rev. Lett.* 85 (2000).
[14] Haldane Speech (April, 2009).
[15] Schweitzer et al. (2009); May, Levin, Sugihara (2006); Haldane Speech (April, 2009).
[16] Haldane Speech (April, 2009).
[17] Watts, D. *Harvard Business Review* June 2009.

One current reform proposal that might address these goals would be designation of certain firms as Tier One Financial Holding Companies (FHCs).[18] Requiring these Tier One FHCs to adhere to stricter and more conservative capital, liquidity, and risk management standards and subjecting them to consolidated supervision and regulation by the Federal Reserve institutes might provide the type of firebreak outlined above. Further, by creating disincentives to becoming a Tier One FHC, such a requirement may reduce the number of high degree nodes, potentially increasing robustness.

Contagion in Networks

The edges that connect nodes in a network can be conduits for "flows" between the nodes—the spread of ideas, of information, of assets, or of risks. Research in network science has shown that the dynamics of *contagion* across a network can be strongly shaped by the network's structure. Two results from this line of research are particularly relevant for contagion in the financial system.

The first is that not all "infected" nodes in a network are equally important in spreading contagion.[19] In networks with the scale-free property, an epidemic will spread widely once it infects a high-degree node, even when the pathogen is not highly contagious.[20] The high-degree nodes become "super-spreaders", so that a small minority of infectious nodes can account for the vast majority of the spread of infection.[21] Certain low-degree nodes can also be critical drivers of contagion, if they connect otherwise distant parts of the network (the so-called "small-world" property).[22] These results highlight the importance that collecting data to map and analyze the structure of financial networks could have for efforts to prevent future financial crises.[23] If the key drivers of contagion in the network could be identified and "vaccinated" in advance (perhaps as discussed above), disruption in one part of the system could be prevented from spreading throughout the network.

A second result involves "social" contagion. In addition to networks of transactional and financial links, the financial system also has another kind of network—*social* networks connecting individual bankers,

[18] *Financial Regulatory Reform: A New Foundation*. Available at http://www.financialstability.gov/docs/regs/FinalReport_web.pdf
[19] Galvani, May (2005).
[20] Watts (2004).
[21] Galvani, May (2005); Haldane Speech (April, 2009).
[22] Watts (2004).
[23] Haldane Speech (April, 2009); Altman, *The New Republic* Oct 9 2009

traders, and board members at financial firms. Social networks have an important effect on financial system dynamics because individual decision makers often pay attention to the actions, decisions, and even beliefs (such as risk perceptions) of others to whom they are linked socially.[24] This can lead to "herd like" behavior driven by social contagion,[25] and can drive "panics" in markets. Empirical evidence suggests that even in well-developed financial markets, informal social networks play a very influential role.[26] Research in network science shows that contagion in these networks can operate somewhat differently than it does in other networks. In a social network, "infection" with an opinion or belief may require confirmation from several other contacts—a message must come from multiple sources in order to be influential.[27] This means that epidemics of social contagion are most likely to occur when the connectivity of the network is neither very sparse nor very dense.[28] If connections are too sparse, messages peter out before spreading very far into the network (just as in a disease epidemic). But if connections are too dense, contagion dies out for a very different reason: novel messages lose influence because they aren't quickly confirmed by the many other connections each node has.[29] Understanding how social networks in the financial system are structured might suggest new avenues for policy to reduce the risk of social contagion.

Resilience in Networks

A network-driven system that has developed to function smoothly in a particular environment may be disrupted if there are abrupt changes to that environment. *Resilience* is the ability of a network to adjust to such a change, working around parts of the system that are no longer well-adapted, and re-wiring itself to restore functionality. This kind of "self-healing" adaptation has been a primary focus of research on ecosystem networks. Research in this area has emphasized the importance of *diversity* in determining the resilience of a system.[30] Selection pressure causes ecosystems to adapt to fit a particular definition of environmental "fitness" at any point in time. If the environment changes suddenly, an ecosystem with sufficient diversity will already contain the seeds of an evolutionary

[24] Watts, (2002); Scherer, C. & Cho, H. *Risk Analysis* 23:2 (2003).
[25] Watts, (2002).
[26] Garmaise, M. & Moskowitz, T. J. *Rev. Finan. Studies* 16(4):1007-1040 (2003).
[27] Centola, Macy (2007).
[28] Watts (2004); Watts (2002).
[29] Ibid.
[30] May, Levin, Sugihara (2006); Bellwood, (2003); Levin, (2008); Levin, Lubchenco (2008).

strategy that can be successful under the new definition of "fitness"; one that has become too homogenous will fail. Markets also provide a form of selection pressure, and financial systems may also require diversity to be resilient in the face of major shifts in the financial environment.[31]

There is growing evidence that the global financial system lost diversity over the last few decades, even as it became more complex.[32] Diversification became widespread practice, but risk management *strategies* became homogenous, and this may have sabotaged the systems' ability to adapt to a sudden shift in market pressures.[33] Thus, an important goal for financial reform might be to provide individual incentive structures that encourage diversification of *strategy* and *function*, not just of investment.

Conclusions

In the wake of the recent financial crisis, comprehensive efforts to understand systemic risk and undertake reform of the financial system should focus not only on financial actors themselves, but also on the ways in which they are connected. The structure of financial networks shapes the systems' dynamics in important ways, and understanding this structure can provide insights into how to prevent future crises. Tools, techniques, and theories from multidisciplinary research in network science can be helpful, but will require more extensive data (such as mapping of formal and informal financial networks) to provide the best insights. A network approach to financial reform offers the potential to suggest reforms that can improve the financial systems' robustness, resilience, and resistance to contagion.

[31] Haldane Speech (April, 2009).
[32] Ibid, May, Levin, Sugihara (2006).
[33] Haldane Speech (April, 2009).