Enforcing the use of exchange markets will make information on prices, volumes and exposures available to regulators and the public — rendering the network structure more transparent. It is also likely to limit the intrinsic problems associated with network interdependence, because the failure of an individual party would be absorbed by the exchange market, rather than being transmitted through the network. However, these markets, if undercapitalized, could also lead to a heightened systemic risk.

In general, well-designed regulatory systems must focus simultaneously on regulating the derivatives network, and mediating the influence of market participants on future policies. It is clear that banks profit from being regarded as too connected, too correlated — and even too complex — to fail, giving them an incentive to engage in excessive risk taking and amplifying the degree of systemic instability. A prudent strategy would therefore not only tame interdependencies and risk taking, but also restrict the power of the financial sector. Unfortunately, lobbying has played — and continues to play — an important role in limiting the development of regulatory structures designed to enhance systemic stability. In any case, reform must be approached dynamically, as market players — pursuing their individual incentives — find ever new ways to circumvent existing regulations at the expense of systemic stability and social welfare.

This certainly amounts to a formidable challenge, from the point of view of both network science and political economy theory, with significant societal implications. Clearly, the development of new network-based metrics to assess systemic risk and evaluate the importance of financial institutions will be of enormous value — forging an already promising union between economists, network scientists and regulators. ❐

Stefano Battiston[1] Guido Caldarelli[2,3] Co-Pierre Georg[4,5] Robert May[5] and Joseph Stiglitz[6] are at [1]ETH Zürich, 8092 Zurich, Switzerland, [2]IMT Alti Studi Lucca, 55100 Lucca, Italy, [3]London Institute for Mathematical Sciences, London W1K 2XF, UK, [4]Deutsche Bundesbank, D-60431 Frankfurt am Main, Germany, [5]Oxford University, Oxford OX1 1HP, UK and [6]Columbia University, New York 10027, USA.*
**e-mail: sbattiston@ethz.ch*

References

1. Buffett, W. E. *Letter to Shareholders 2002* (Berkshire Hathaway Inc., 2002); available at http://www.berkshirehathaway.com/letters/2002pdf.pdf
2. Stiglitz, J. E. *Am. Econ. Rev.* **100,** 388–392 (2010).
3. Battiston, S., Gatti, D. D., Gallegati, M., Greenwald, B. C. N. & Stiglitz, J. E. *J. Econ. Dyn. Contr.* **36,** 1121–1141 (2012).
4. Haldane, A. G. & May, R. M. *Nature* **469,** 351–355 (2011).
5. Corrigan, E. G. *Financial Market Structure: A Longer View.* (Federal Reserve Bank of New York, 1987).
6. Stiglitz, J. E. in *Financial Economics: Essays in Honor of Paul Cootner* (eds Sharpe, W. F. & Cootner, C. M.) 118–158 (Prentice Hall, 1982).
7. Battiston, S., Puliga, M., Kaushik, R., Tasca, P. & Caldarelli, G. *Sci. Rep.* **2,** 541 (2012).
8. May, R. M. *Nature* **238,** 413–414 (1972).

Acknowledgements

The authors acknowledge support from the European FET Open Project FOC 'Forecasting Financial Crises' (No. 255987) and from the Working Group on Networks and Systemic risk, part of the Institute for New Economic Thinking's Financial Stability Research Program.

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The views expressed in this Commentary do not necessarily reflect the views of Deutsche Bundesbank or the European System of Central Banks.

Reconstructing a credit network

Guido Caldarelli, Alessandro Chessa, Andrea Gabrielli, Fabio Pammolli and Michelangelo Puliga

The science of complex networks can be usefully applied in finance, although there is limited data available with which to develop our understanding. All is not lost, however: ideas from statistical physics make it possible to reconstruct details of a financial network from partial sets of information.

Between financial systems or agents there may be reciprocal ties, of irregular number and weight, which create a highly connected structure with the features of a complex network[1–4] — those ties may be in the form of liability, exposure, ownership or simple correlation. Together these factors describe a topology for which the diffusion dynamics — of information, or of financial distress — among the institutions, or nodes, of the network is not straightforward, and can be quite unexpected.

Distress propagating in a financial network can cause bankruptcies and spread distrust, thereby changing the shape and the topology of connections. This in turn can give rise to a self-sustained process of failures, in an often-unstoppable domino effect. In such a context, risk exposure is affected not only by the quality of an institution's counterparts, but also by the quality of many other players, through complex chains of actions and reactions and with a corresponding increase of uncertainty, risk aversion and risk shifting, liquidity evaporation, collateral shortages and so on[5].

Given that a network's diffusion properties are deeply entwined with its topology, it is crucial to focus on the precise structure of the network. For example, even a few randomly placed shortcuts on a regular grid can create the so-called small-world effect — a radical reduction of the distances between regions of the system that are otherwise far apart — which is one of the main reasons for the surprising velocity of distress propagation. It is therefore of fundamental importance to know how much the results of any analysis depend on exact knowledge of the network structure.

The network structure of financial systems is central to many of the processes and mechanisms that come into play during a crisis, and it has become a key motivation for some of the 'macroprudential' policies[6] developed during the current financial crisis, from bailouts to asset purchase programmes. Furthermore, when evaluating systemic risk for a specific financial institution, we must also consider the kind of ties it has, be they lending, exposure, correlation or ownership. Some ties result in more stable configurations than others, and this multilevel structure — which lacks an adequate mathematical representation at present— allows distress to propagate in environments that otherwise seem solid.

Missing links

Despite all that could be learned from an evaluation of systemic risk from topology, there is a major problem: lack of relevant information. Regulators, network scientists and economists are trying to get access to data on financial institutions that are confidential at present. At the same time, they are trying to find the best way to merge the different partial snapshots of financial networks that are available. Not surprisingly, the reconstruction of complex networks from partial information is one of the outstanding problems in the field.

Standard methods (such as maximum-entropy algorithms) have so far proved to be of limited effect in this respect, although they can reveal hierarchical structures[7] in a network. The main problem for these approaches is that the connectivity of a real network is, in general, not reproducible. However, an alternative approach[8] makes use of the fact that some of the properties of these systems are stable, at least in a statistical sense. In this way it is possible to tackle the problem by bringing together complex-network modelling, suitable generalizations of some concepts from statistical physics (equilibrium statistical ensembles, for example) and tools from mathematical statistics (such as the maximum-likelihood method). Using these ingredients, the fundamental statistical features of some important complex networks — real and synthetic — have been reconstructed in considerable detail, and the propagation of distress has been explored using models that have only a limited number of parameters[8].

One of the most recent techniques makes explicit use of the so-called fitness model[9]. This model describes all the situations in which there is, or there is expected to be, a strong correlation between the connectivity (the number of links) and a non-topological feature (fitness) for each node where 'fitness' can be the total capital of an institution in a financial network, and is typically Pareto-distributed in real networks.

Even if only a small portion of a system is known, it becomes possible to reconstruct the statistical properties of the whole in some detail. For instance, this is used in the reconstruction of the World Trade Web (WTW), where the nodes are countries characterized by their GDP (ref. 10), and in financial networks of interbank lending, whose nodes are banks characterized by their total volume of exchanges. In both cases, the most important statistical features of the networks have been determined by knowing the connectivity of less than 10% of the total nodes in the networks.

However, all of these methods can reconstruct only macroscopic or statistical properties. A larger initial set of information is needed to recover the actual microscopic configuration of the system — which would be much more useful to a policymaker attempting to take necessary countermeasures in the face of a crisis. The data are certainly out there, and financial institutions should be encouraged to release them by regulators and by governments

Network by proxy

A different but related approach is to reconstruct the network using a proxy for the information that is missing. This is how the 'DebtRank'[11] was computed for financial institutions during the recent financial crisis. DebtRank is a measure of financial centrality in the banking network, taking into account the impact of the distress of a node across the whole network; reciprocal equity stakes are used as a proxy for the unknown — and possibly uncollectable — information on the network of mutual exposures.

A similar method works for the network of credit default swaps (CDS; the buyer of a CDS is compensated by the seller in the event of a loan default) across financial institutions. In the case of CDS, the problem is particularly acute; despite the crucial role of these products in the stability of markets over the last decade, there is rarely information available on the structure these networks. The interdependencies can be represented by computing the cross-correlation of CDS pairs; even considering only the couples of CDS with enough statistics, it is possible to generate useful insight into the stability of the systems.

Irrespective of the approach used, the importance of network reconstruction in the analysis of financial systems is clear. Recent theoretical advances in network analysis and modelling provide crucial tools that analysts and policymakers will be able to use in the evaluation and control of financial systems. ❐

Guido Caldarelli[1,2,3], Alessandro Chessa[1], Fabio Pammolli[1], Andrea Gabrielli[3] and Michelangelo Puliga[4] are at the IMT Alti Studi Lucca, Piazza S. Ponziano 6, 55100 Lucca, Italy, [2]London Institute for Mathematical Sciences, London W1K 2XF, UK, [3]ISC-CNR, UOS Sapienza, Dipartimento di Fisica, Università Sapienza, Piazzale Moro 2, 00185 Roma, Italy and [4]ETH Zürich, 8092 Zurich, Switzerland.*
**e-mail: guido.caldarelli@imtlucca.it*

References

1. Bonanno, G., Caldarelli, G., Lillo, F. & Mantegna, R. N. *Phys. Rev. E* **68,** 046130 (2003).
2. Garas, A., Argyrakis, P. & Havlin, S. *Eur. Phys. J. B* **63,** 265–271 (2008).
3. Kaushik, R. & Battiston, S. Preprint at http://arXiv.org/abs/1205.0976 (2012).
4. Kullmann, L., Kertész, J. & Kaski, K. *Phys. Rev. E* **66,** 026125 (2002).
5. Caballero, R. J. *J. Econ. Perspect.* **24,** 85–102 (Fall 2010).
6. De Nicolò, G., Favara, G. & Ratnovski, L. *Externalities and Macroprudential Policy* SDN/12/05 (International Monetary Fund, 2012).
7. Clauset, A., Moore, C. & Newman, M. E. J. *Nature* **453,** 98–101 (2008).
8. Musmeci, N., Battiston, S., Caldarelli, G., Puliga, M. & Gabrielli, A. Preprint at http://arXiv.org/abs/1209.6459 (2012).
9. Caldarelli, G., Capocci, A., De Los Rios, P. & Muñoz, M-A. *Phys. Rev. Lett.* **89,** 258702 (2002).
10. Garlaschelli, D. & Loffredo, M-I. D. *Phys. Rev. Lett.* **93,** 188701 (2004).
11. Battiston, S., Puliga, M., Kaushik, R., Tasca, P. & Caldarelli, G. *Sci. Rep.* **2,** 541 (2012).

Acknowledgements

The authors acknowledge support from the European FET Open Project FOC 'Forecasting Financial Crises' (No. 255987) and from the Italian PNR project.

The power to control

Marco Galbiati, Danilo Delpini and Stefano Battiston

Understanding something of the complexity of a financial network is one thing, influencing the behaviour of that system is another. But new tools from network science define a notion of 'controllability' that, coupled with 'centrality', could prove useful to economists and financial regulators.

The financial crisis that erupted in 2008 has made plain the shortcomings of old paradigms in economics and finance, and researchers have turned to other disciplines to seek fresh insight. Network science — thoroughly studied in mathematics and physics for decades — has thus made its way into economics, with financial institutions imagined as the nodes of a network, linked by financial flows, contracts or other interactions. Two main kinds of tool have been provided for the study of financial networks: the first is network statistics, which summarize global properties of a network in one (or few)