This is just an illustration of how information technology can help in quantifying subtle collective behaviours. In the context of economics, such experiments could be enormously valuable. For example, it has been shown[11] that the volume of transactions of a company at a certain time is correlated to the volume of searches related to that company at the previous time-step — the reason is unclear, but it could be that the number of searches is a rough measure of the interest (generated by worry or enthusiasm) in that company. Notably, similar systems have been employed to predict other phenomena, such as flu epidemics[12].

The coincidence of new theoretical tools, a wealth of new data and the will to change paradigms provides a chance for a leap forward in our understanding of financial and economic systems, with an attendant increase in our capacity to manage them and avoid the worst problems. One important challenge, among many others, is to make scientific advances both available to the public, and useful for policymakers. No one believes that better science alone will make economic crises a thing of the past, or allow the precise prediction of the economic or financial future. But better models that take into account feedbacks and network dynamics should greatly boost the ability of everyone to foresee the kinds of events to which markets and economies are prone, to understand the conditions that are likely to create them, and to offer some guidance on how to avoid those circumstances. Even a little more knowledge could be of great value.

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Complex derivatives

Stefano Battiston, Guido Caldarelli, Co-Pierre Georg, Robert May and Joseph Stiglitz

The intrinsic complexity of the financial derivatives market has emerged as both an incentive to engage in it, and a key source of its inherent instability. Regulators now faced with the challenge of taming this beast may find inspiration in the budding science of complex systems.

When financial derivatives were cast[1] in 2002 as latent 'weapons of mass destruction', one might have expected the world at large to sit up and listen — particularly in the wake of subsequent events that led to the financial crisis of 2008. Instead, the derivatives market continues to grow in size and complexity (Fig. 1), spawning a new generation of financial innovations, and raising concerns about its potential impact on the economy as a whole.

A derivative instrument is a financial contract between two parties, in which the value of the payoff is derived from the value of another financial instrument or asset, called the underlying entity. In some cases, this contract acts as a kind of insurance: in a credit default swap, for example, a lender might buy protection from a third party to insure against the default of the borrower. However, unlike conventional insurance, in which a person necessarily owns the house she wants to insure, derivatives can be negotiated on any underlying entity — meaning anyone could take out insurance on the house in question. Speculation therefore emerges as another reason to trade in derivatives.

By engaging in a speculative derivatives market, players can potentially amplify their gains, which is arguably the most plausible explanation for the proliferation of derivatives in recent years. Needless to say, losses are also amplified. Unlike bets on, say, dice — where the chances of the outcome are not affected by the bet itself — the more market players bet on the default of a country, the more likely the default becomes. Eventually the game becomes a self-fulfilling prophecy, as in a bank run, where if each party believes that others will withdraw their money from the bank, it pays each to do so. More perversely, in some cases parties have incentives (and opportunities) to precipitate these events, by spreading rumours or by manipulating the prices on which the derivatives are contingent — a situation seen most recently in the London Interbank Offered Rate (LIBOR) affair.

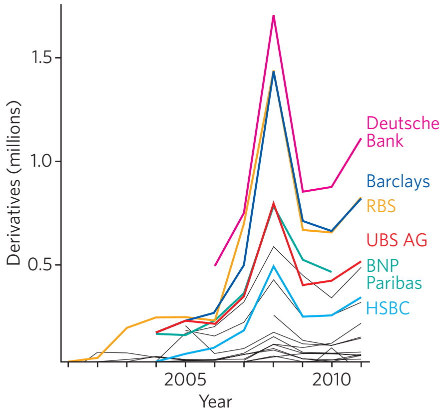

Figure 1 | The largest players in the derivatives market. Despite a downturn following the 2008 financial crisis, the volume of derivative contracts for 30 top market players continues to increase, with the 7 biggest labelled in colour. Data from Bankscope © 2013 Bureau van Dijk.

Proponents of derivatives have long argued that these instruments help to stabilize markets by distributing risk, but it has been shown recently that in many situations risk sharing can also lead to instabilities[2,3].

Market as network

Players engaging in the derivatives market can enter into an unlimited number of contracts with other parties, so the market can be seen as a complex financial network, in which interactions between the nodes are nonlinear[4]. A derivative contract can itself be made arbitrarily complex — it has been estimated[5] that if one of these contracts were presented in the older idiom of a 'prospectus', it could run to something like 10^9 pages. Derivatives can be constructed recursively, such that one derivative underlies another, and the payoff can depend on any imaginable set of events — say, the weather in London three months from now. This means that in modelling the market as a network, representing banks as nodes and contracts as links, one quickly finds that both nodes and links can depend on the state of other nodes in the network. This requires building an extra level of complexity into the network models with which physicists have become familiar. Describing the dynamics of such a system is enough of a challenge for network science — apart from the problems posed by predicting its behaviour and ensuring its robustness to failure.

The network is further complicated by a lack of transparency. A large fraction of trades on the derivatives network occur over-the-counter (OTC), meaning they are privately negotiated between two parties without the need for an intermediary. Worldwide, the total volume of OTC derivatives increased steadily from US$100 trillion in 2000 to over US$500 trillion in 2011 — more than five times the global gross domestic product. Despite the huge volumes involved, all OTC contracts are confidential and are not disclosed, rendering the structure of the network largely obscure — and hindering our understanding of the derivatives market as a complex system. Indeed, these characteristics make the market vulnerable to the build-up of instabilities that suddenly, and unpredictably, induce cascades of the sort shared by many nonlinear phenomena in physics.

The European Commission has recently adopted new reporting standards that may improve the situation, and could be enforced as early as the end of 2013. Without such measures, this lack of transparency may itself contribute to an intrinsic financial instability, setting aside the problems associated with regulators having restricted access to information. Indeed, when market participants come to believe that there are large asymmetries of information, they may not trade with each other. This so-called no-trade theorem[6] — sometimes referred to as a drying up of liquidity—is precisely what happened in 2007–2008: the interbank lending market dried up, and banks refused to lend to each other, forming a key factor in prompting the global financial crisis.

Paradoxically, this information asymmetry is one of the main incentives for market players to engage in a derivatives market that is so complex. Derivatives, especially OTC derivatives, are not easy to price, and their evaluation relies on models. This makes it harder to estimate the risk of the deal, resulting in an information asymmetry that can be exploited at the expense of other parties. In markets with full rationality, such contracts wouldn't be executed — the party with less information would simply refuse to sign[6]. But there is ample evidence in the literature of both economics and psychology to suggest that individuals routinely overestimate their own knowledge.

Another way that financial institutions profit from complexity stems from their need to be perceived as systemically important, to guarantee governmental rescue in the face of crisis. Systemic importance is no longer regarded as simply a matter of size — of banks being 'too big to fail'. In complex networks, an initial impact can be greatly amplified by cascading along the network's connections. A correspondence between cascade sizes and 'centrality' — quantifying a node's importance in the network — has therefore given rise to the idea of a bank being 'too central to fail', which can be captured by the DebtRank indicator[7]. Related notions of 'too connected to fail' or 'too correlated to fail' are also now beginning to be factored into governmental subsidization of the financial sector.

But the perceived benefits of complexity are certainly not restricted to the network players that fulfil these key roles. The complexity of both the instruments and the network structure can render peripheral institutions virtually indistinguishable from the core of institutions that are guaranteed government subsidy — meaning that risk-averse governments will also come to their rescue. If the market were more transparent, competition would be stronger, and profits would be eroded. Thus, being 'too complex to fail' may pay off well for individual banks, even if it undermines systemic performance.

And there remains an even less savoury use of complexity. Derivatives can be used to manipulate accounts to make things seem better at one moment, at the cost of making things look worse at another. The most notorious example of this is a recent case of financial institutions using derivatives to make Greece's financial position appear strong enough for membership of the Eurozone.

Complexity and instability

Early studies of ecosystem stability erroneously implied that greater complexity — given by more species interacting more extensively — automatically conferred greater robustness. But subsequent investigation has shown that, in general, the converse is true. This is encapsulated by the May–Wigner theorem[8], which conveys the fact that increasing complexity in a network inevitably leads to its destabilization. One might think of this as a formalization of the everyday idea that complicating matters tends to multiply the number of ways that things can go wrong.

It now seems that the proliferation of financial instruments induces strong fluctuations and instabilities for similar reasons[4]. The basis for pricing complex derivatives makes several conventional assumptions that amount to the notion that trading activity does not feed back on the dynamical behaviour of markets. This idealized (and unrealistic) model can have the effect of masking potential instabilities in markets. A more detailed picture, taking into account the effects of individual trades on prices, reveals the onset of singularities as the number of financial instruments increases[4]. The continued development of myriad new instruments and the steady increase in the number and connectivity of market players therefore seem to give rise to the conditions stipulated by the May–Wigner theorem.

The instability is not necessarily easy to understand from the idealized model. The idea is that once there are enough derivative instruments available to meet the demands of all players, the market is essentially complete. But as long as there is a monetary incentive to create new instruments, banks will continue to do so. Subsequent trades will then serve only to increase the complexity of the network at the expense of stability. The irony is that if the market were in fact complete, these contracts would have no real effect. But under the real-world conditions of an incomplete market characterized by considerable complexity, these trades, even if individually rational, may undermine systemic market performance.

On the other hand, ensuring a diversity of players and restricting the scope of business in which they can engage may emerge, we believe, as one of the few ways of limiting the incentives of market participants to engage in highly correlated behaviour — a practice that would otherwise lead naturally to systemic risk.

Regulate to accumulate

The fact that derivatives may not only hamper the assessment of systemic risk, but also foster its emergence, has spurred a debate in recent years about the global financial architecture and its possible regulation. Four key reforms have been proposed, emphasizing the need for transparency and exchange markets, targeting the implicit subsidies that government-insured entities receive from the public and removing the priority given to derivative instruments in bankruptcy.

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. ❐

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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