especially in the need to identify conditions that dispose a system to be knocked from seeming stability into another, less happy state.

'Tipping points', 'thresholds and breakpoints', 'regime shifts' — all are terms that describe the flip of a complex dynamical system from one state to another. For banking and other financial institutions, the Wall Street Crash of 1929 and the Great Depression epitomize such an event. These days, the increasingly complicated and globally interlinked financial markets are no less immune to such system-wide (systemic) threats. Who knows, for instance, how the present concern over sub-prime loans will pan out?

Well before this recent crisis emerged, the US National Academies/National Research Council and the Federal Reserve Bank of New York collaborated[1] on an initiative to "stimulate fresh thinking on systemic risk". The main event was a high-level conference held in May 2006, which brought together experts from various backgrounds to explore parallels between systemic risk in the financial sector and in selected domains in engineering, ecology and other fields of science. The resulting report[1] was published late last year and makes stimulating reading.

Catastrophic changes in the overall state of a system can ultimately derive from how it is organized — from feedback mechanisms within it, and from linkages that are latent and often unrecognized. The change may be initiated by some obvious external event, such as a war, but is more usually triggered by a seemingly minor happenstance or even an unsubstantial rumour. Once set in motion, however, such changes can become explosive and afterwards will typically exhibit some form of hysteresis, such that recovery is much slower than the collapse. In extreme cases, within this medley of interests. For instance, to what extent can mechanisms that enhance stability against inevitable minor fluctuations, in inflation, interest rates or share price for example, in other contexts perversely predispose towards full-scale collapse?

Two particularly illuminating questions about priorities in risk management emerge from the report. First, how much money is spent on studying systemic risk as compared with that spent on conventional risk management in individual firms? Second, how expensive is a systemic-risk event to a national or global economy (examples being the stock market crash of 1987, or the turmoil of 1998 associated with the Russian loan default, and the subsequent collapse of the hedge fund Long-Term Capital Management)? The answer to the first question is “comparatively very little”; to the second, “hugely expensive”.

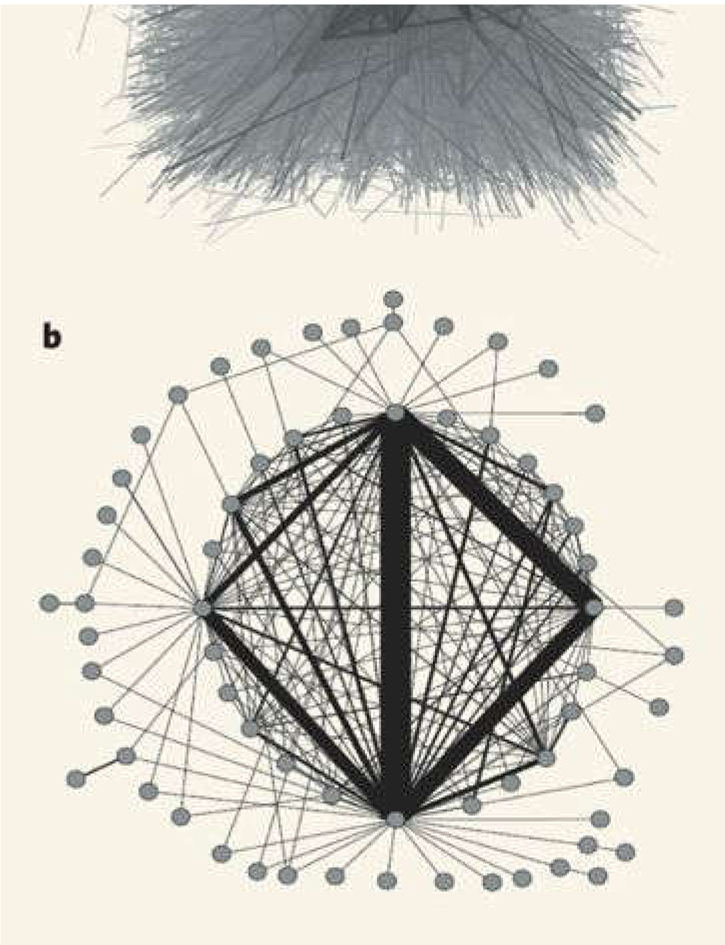
An analogous situation exists within fisheries management. For the past half-century, investments in fisheries science have focused on management on a species-by-species basis (analogous to single-firm risk analysis). Especially with collapses of some major fisheries, however, this approach is giving way to the view that such models may be fundamentally incomplete, and that the wider ecosystem and environmental context (by analogy, the full banking and market system) are required for informed decision-making. It is an example of a trend in many areas of applied science acknowledging the need for a larger-system perspective.

But to what extent can study of ecosystems inform the design of financial networks in, for instance, their robustness against perturbation? Ecosystems are robust by virtue of their continued existence. They have survived eons of change —

An example of this kind emerges from work on the network structure of communities of pollinators and the plants they pollinate[3]. These networks are disassortative, in the sense that highly connected 'large' nodes tend to have their connections disproportionately with 'small' nodes; conversely, small nodes connect with disproportionately few large ones. The authors[3] show that such disassortative networks tend to confer a significant degree of stability against disturbance. More generally, ecologists and others have long suggested that modularity — the degree to which the nodes of a system can be decoupled into relatively discrete components — can promote robustness. Thus, a basic principle in the management of forest fires and epidemics is that if there is strong interconnection among all elements, a perturbation will encounter nothing to stop it from spreading. But once the system is appropriately compartmentalized — by firebreaks, or vaccination of 'superspreaders' — disturbance or risk is more easily countered.

As the report[1] notes, this is a complicated question, because modularity will often involve a trade-off between local and systemic risk. Moreover, the wrong compartmentalization in financial markets could preclude stabilizing feedbacks, such as mechanisms for maintaining liquidity of cash flows through the financial system, where fragmentation leading to illiquidity could actually increase systemic risk (as in the bank runs leading to the Great Depression). Redundancy of components and pathways, in which one can substitute for another, is also a key element in the robustness of complex systems, and effective redundancy is not independent of modularity.

In short, the dynamical implications of the topology of financial networks emerge as good candidates for further research. This is a lively field: the interplay between on an average day (ecologists studying food webs can only dream of such high-quality data). The authors[6] find the connectivity of this network — the ratio of the number of banks or nodes connected by one or more transfers to the total number of possible connections (essentially $0.5n^2$, where n is the number of banks) — is very low, around 0.003. This connectivity is characterized by a relatively small number of strong flows (many transfers) between nodes, with the vast majority of linkages being weak to zero (few to no flows). On a daily basis, 75% of the payment flows involve fewer than 0.1% of the nodes, and only 0.3% of the observed linkages between nodes (which are already extremely sparse). This kind of inequitability in linkage strengths (with most links being weak) is thought to predominate and help stabilize some ecological networks.



a, This 'furball' depiction takes in thousands of banks and tens of thousands of links representing US$1.2 trillion in daily transactions. **b,** The core of the network, with 66 banks accounting for 75% of the daily value of transfers, and with 25 of the banks being completely connected. Every participating bank, and every transaction, in the full network is known (akin to an ecologist knowing all species in an ecosystem, and all flows of energy and nutrients). So the behaviour of the system can be analysed in great detail, on different timescales and, for example, in response to events such as 9/11. (Reproduced from ref. 9.)

Overall, the topology of this Fedwire network is highly disassortative: large banks were disproportionately connected to small banks, and vice versa; the average bank

These insights must be viewed against the reality that the payments system may not always be the relevant network for understanding systemic events. As the report notes, political and social networks may emerge to play a larger role in liquidity transactions and/or in the spread of rumours, which can ultimately influence the tides of fear and greed, and thence consensus valuation of markets. In this way the ever-changing finance problem, despite having certain resemblances to that posed in understanding ecosystems, is different from the fixed networks considered in physical sciences. The report puts it succinctly: "the odds on a 100-year storm do not change because people think that such a storm has become more likely". Emphasizing the point is this observation[1]:

"... in contrast to management of the electric power grid, there are only coarse or indirect options for control of the financial system. The tools available to policymakers — such as those used by central banks — are designed to modify individual incentives and individual behaviors in ways that will support the collective good. Such top-down efforts to influence individual behaviors can often be effective, but it is still difficult to control the spread of panic behavior or to manage financial crises in an optimal way. Within the financial system, robustness is something that emerges; it cannot be engineered."

Thus, although the study of payment flows is of immediate interest to central bankers, it may miss an essential aspect of systemic risk, namely the 'contagion dynamics' of public perceptions and asset valuation associated with the interaction of balance-sheets (the mutual financial obligations and exposures that link companies). For example, how contagious are inflated valuations of Internet stocks? Are there hidden, mutually dependent risks associated with such high valuations? It understanding the ecology of market robustness and its potential vulnerability to collapse.

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