NEWS & VIEWS

COMPLEX SYSTEMS

Ecology for bankers

Robert M. May, Simon A. Levin and George Sugihara

There is common ground in analysing financial systems and ecosystems, 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, the changes may be irreversible.

As the report[1] emphasizes, the potential for such large-scale catastrophic failures is widely applicable: for global climate change, as the greenhouse blanket thickens; for 'ecosystem services', as species are removed; for fisheries, as stocks are overexploited; and for electrical grids or the Internet, as increasing demands are placed on both. With its eye ultimately on the banking system, the report concentrates on the possibility of finding common principles and lessons learned 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?

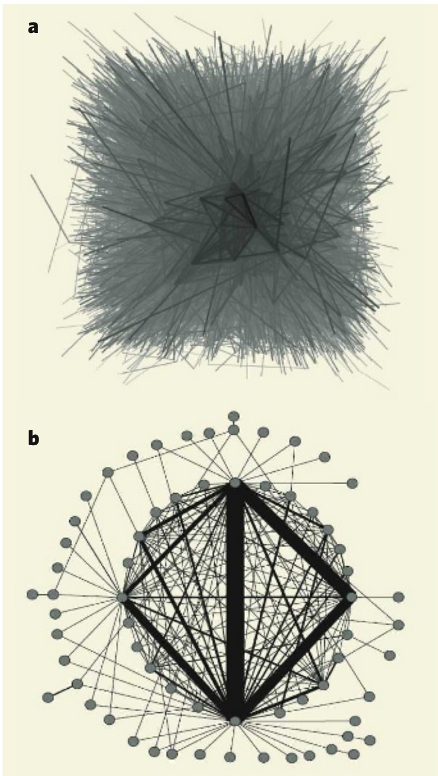

Figure 1 | The Fedwire interbank payment network. a, This 'furball' depiction takes in thousands of banks and tens of thousands of links representing US$1.2 trillion in daily transactions. **b,** The core of the network, with 66 banks accounting for 75% of the daily value of transfers, and with 25 of 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.)

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 — continental drift, climate fluctuations, movement and evolution of constituent species — and show some remarkable constancies in structure that have apparently persisted for hundreds of millions of years: witness, for example, the constancy in predator–prey ratios in different situations[2]. Identifying structural attributes shared by these diverse systems that have survived rare systemic events, or have indeed been shaped by them, could provide clues about which characteristics of complex systems correlate with a high degree of robustness.

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.

50 & 100 YEARS AGO

50 YEARS AGO

It was natural that the genetic transformation of bacteria effected by the introduction of foreign deoxyribonucleic acid should lead to speculation as to whether the phenomenon could also be induced in higher forms. That similar treatment should be capable not only of altering the racial characteristics of the growing vertebrate but that such changes would also be heritable seemed one of the least likely outcomes of such an experiment. Recently published reports by Benoit *et al.* state that they have succeeded in changing the characteristics of ducks of one breed by injections of deoxyribonucleic acid from another, and that the modifications continued to be identifiable in the progeny of the treated birds. Because of the importance that must be attached to such revolutionary claims, and in the absence, as yet, of substantive evidence from repeat experiments, the work of Benoit and his colleagues should be subjected to critical scrutiny.
From *Nature* 22 February 1958.

100 YEARS AGO

In the February issue of *British Birds* the editors discuss certain allegations against the black-headed gull which formed the subject of notice in the previous issue. Without entering into the controversy, we may notice that the allegations have induced two county councils in Scotland to strike gulls of all kinds out of the protected list. In another paragraph the editors refer to the subject of "luminous owls." In their opinion, the luminosity is most probably to be attributed to phosphorescent bacteria derived from decaying wood. It may, however, be due either to a phosphorescent feather-fungus (akin to one known to occur in geese) or to a diseased condition of the oil-gland, whereby the oil is more abundant than usual, and so abnormal in its nature as to become luminous on exposure to the air.
From *Nature* 20 February 1908.

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 network topology and random or targeted 'attack' has also provided insights for the control of infectious diseases[4] and the defence of networks such as the Internet[5].

Following this theme, the Federal Reserve Bank of New York commissioned a study[6] of the topology of interbank payment flows within the US Fedwire service (Fig. 1); this is a real-time settlement system, operated by the Federal Reserve System, within which some 9,500 participating banks transfer funds. The sample from this network amounted to around 700,000 transfers, with just over 5,000 banks involved 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.

Overall, the topology of this Fedwire network is highly disassortative: large banks were disproportionately connected to small banks, and vice versa; the average bank was connected to 15 others, but this does not give an accurate idea of the reality in which most banks have only a few connections while a small number of 'hubs' have thousands. These strongly nonrandom and disassortative characteristics of the bank-transfer network are, as noted above, shared by some ecological systems. They also resonate with theoretical studies suggesting that sparseness of strong linkages can confer greater stability in systems whose components (nodes, banks, species) have some self-regulation[7,8].

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 could be useful to examine the dynamic network of balance-sheets, and if possible to quantify the interactive effects of valuations, credit policies, hedging and so on among financial institutions, especially investment banks. Such balance-sheet networks could be helpful in studying the effects of asset-pricing bubbles, credit crises and the poorly understood but potentially worrying effects of the current widespread use of derivatives (futures and options) and dynamic hedging by investment banks to manage risk on the fly. Whatever the case, it seems that the ephemeral networks that define financial reality and global markets are a key to understanding the ecology of market robustness and its potential vulnerability to collapse. ■

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MATERIALS SCIENCE

The gift of healing

Justin L. Mynar and Takuzo Aida

Synthesis of a rubber-like material that can be recycled might not seem exciting. But one that can also repeatedly repair itself at room temperature, without adhesives, really stretches the imagination.

When the Spanish conquistadores first witnessed the Aztec game played with a bouncing rubber ball, they thought that such balls must be possessed by evil spirits. Imagine their reaction if, on cutting the ball in half, it was made as good as new simply by pressing the two halves together without heat or adhesives.

Even today, such a feat would have a touch of magic about it. But this is what Cordier *et al.* (page 977 of this issue[1]) have achieved. They have synthesized a material with the properties of rubber that, when severed, can self-heal at room temperature if the severed surfaces are brought together. The underlying mechanism is that of 'supramolecular assembly', which operates through non-covalent interactions. The material maintains its mechanical features even when repeatedly broken and repaired.

Self-healing materials have long been the subject of research, with many groups exploring systems that undergo reversible transformation from individual components to a composite, or systems that incorporate self-healing materials within the composite. The potential applications are manifold — tears in clothes that effectively stitch themselves together; long-lasting coatings and paints for houses and cars; and, to take one example on the medical front, self-repairing artificial bone and cartilage.

One of the milestones in this field came from White *et al.*[2], whose approach involved mixing microcapsules containing healing monomers into an epoxy polymer matrix that contains a catalyst. When a break occurs, the microcapsules are destroyed, releasing the monomers into the crack; there they come into contact with the catalyst, triggering a polymerization reaction that swells the healing material until the crack is closed. This system needs no intervention when healing. But if a fracture occurs again in the same place, there is less or no healing agent to effect a repair. This problem is being addressed by the use of 'microvascularization' to resupply healing agents, but it is difficult to construct the necessary channels, and the approach is limited to small-scale operations[3].

Chen *et al.*[4] developed another strategy. They used polymers modified with moieties that undergo reversible cross-linking — meaning that varying decomposition and formation of the composite occurs, thus creating a self-healing system. An advantage of 'reversible systems' such as this is the ability to self-mend repeatedly, even after several fractures have occurred at the same place. But it is not easy to synthesize these polymers, and an external stimulus (in this case, heat) is required. The authors claimed that the system can repair itself under mild conditions, but the temperatures used were well above room temperature.

The beauty of Cordier and colleagues' work[1] is the clever use of supramolecular assembly to create a material that not only has the properties of rubber, but is also self-healing. Conventional rubbers are typically long-chain, cross-linked polymers that can stretch then recover to their original size and shape. Instead, Cordier *et al.* achieve those properties with a mixture of small ditopic molecules (those that can associate with two other molecules) and multitopic molecules (which can associate with more than two). The resulting supramolecular network exhibits partial cross-linking, through hydrogen bonds, which means that the material does not crystallize and is elastic. When it fractures, the active ends of the hydrogen-bond network are exposed because the strength of the self-assembly association is lower than that of covalent bonds. The broken ends can be thought of as living, and can be recombined by simply bringing them together (Fig. 1): microscopic association produces macroscopic healing.

The longer the time for which the broken ends are brought together, the more bridging associations form and the better the recovered extensibility. The elapsed time between severing and bringing the ends together also matters: the molecules at each end will start to couple with their neighbours, eventually deactivating the ends. But at room temperature it is a week before the ability to self-repair is lost. The only limitation of the material is that one must bring the two ends together and allow at least 15 minutes for self-repair.

It is satisfying to see the strategy of supramolecular assembly increasingly being turned to practical ends. Previous developments include that described by Meijer and colleagues[5], who have produced materials that take advantage of the fact that reversible, non-covalent forces are sensitive to many different environmental factors. Because these materials are comparatively easy to make and reprocess,

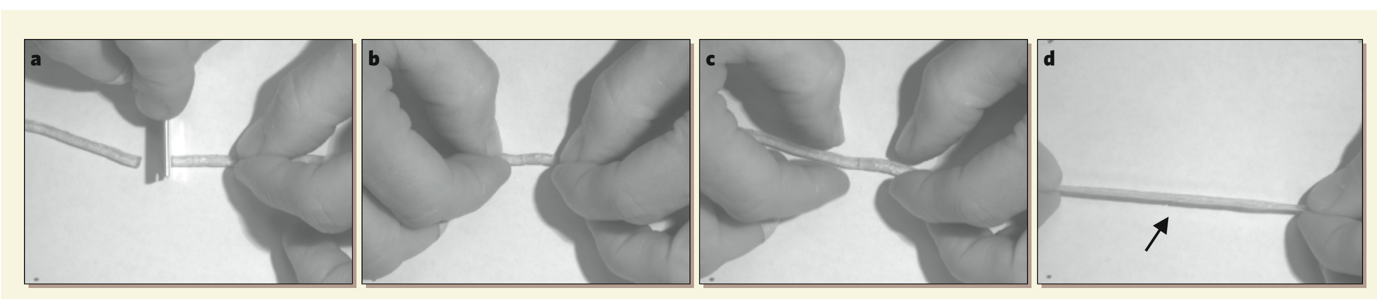

Figure 1 | On the mend. This sequence of photos, produced by Cordier *et al.*[1], shows self-healing being put to the test. **a–d**, Cut, join, mend, stretch.