NEWS & VIEWS

COMPLEX NETWORKS

The fragility of interdependency

Alessandro Vespignani

A study of failures in interconnected networks highlights the vulnerability of tightly coupled infrastructures and shows the need to consider mutually dependent network properties in designing resilient systems.

Life as we know it in the modern world is more and more dependent on the intricate web of critical infrastructure systems. The failure or damage of electric power, telecommunications, transportation and water-supply systems would cause huge social disruption, probably out of all proportion to the actual physical damage. Although urban societies rely on each individual infrastructure, recent disasters ranging from hurricanes to large-scale power outages and terrorist attacks have shown that the most dangerous vulnerability is hiding in the many interdependencies across different infrastructures[1,2]. Relatively localized damage in one system may lead to failure in another, triggering a disruptive avalanche of cascading and escalating failures.

Understanding the fragility induced by multiple interdependencies is one of the major challenges in the design of resilient infrastructures[1,2]. On page 1025 of this issue, Buldyrev and co-workers[3] lay out the framework for the analysis of catastrophic failures in interdependent networks. Their work, building on the 'percolation analysis' of two mutually dependent networks, highlights the subtleties of this problem and clearly shows that systems made of interdependent networks, such as transport networks (Fig. 1), can be intrinsically more fragile than each network in isolation.

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Figure 1 | Interconnected networks of human mobility in North America. The blue network represents short-range commuting flows by car, train and other means of transportation and transport infrastructures. Yellow-to-red lines denote airline flows for a few selected cities; red corresponds to greater traffic intensity. Population density is identified on the grey/white colour scale, with white corresponding to areas of higher density. All features in this map were obtained from real data[10].

Over the past two decades it has become obvious that the analysis and understanding of large-scale infrastructures transcend engineering and design issues. Although generally subject to local design, engineering and optimization, infrastructures evolve globally through unplanned aggregation of isolated parts, adaptation to anticipated and unanticipated demands, and the transformation of services according to evolving social needs. A classic example is the physical Internet made of computers and their physical connections, which, as the result of an unsupervised and exponential growth, has become one of the first human artefacts that we study as a natural phenomenon by devising experiments aimed at tracing its network structure and geographical distribution[4,5].

Viewed from this perspective, critical infrastructures are complex systems for which it is generally impossible to abstract the global behaviour from the analysis of single components, especially under conditions such as failures and disasters. Work on the mechanics and performance of components, new materials and innovative engineering principles are crucial in the design of resilient infrastructures, but there is also a need to understand the general principles leading to the complex global architecture of these systems and their ability to withstand failures, natural hazards and man-made disasters. In this context, a large body of research has shown that most real-world infrastructure networks present globally dynamic self-organization and a high level of heterogeneity characterized by statistical distributions that vary over several orders of magnitude[6,7]. In principle, these global and heterogeneous properties may have a strong impact on the vulnerability of large-scale systems as well as on the strategies that might be used to contain the spreading of failures in them. Such an impact has recently been studied in a global-behaviour perspective using the framework of complex networks[8–10].

Although investigations of the resilience of complex networks have triggered enormous interest and debate, most studies have focused on single, isolated networks. Such a situation is more the exception than the norm, however. Infrastructures show a large number of interdependencies of differing types: physical interdependency when energy, material or people flow from one infrastructure to another; cyber interdependency when information is transmitted or exchanged; geographical interdependency such as the close spatial proximity of the elements of the infrastructure; logical interdependency such as financial dependence, political coordination and so on. All of these interdependencies are the nexus allowing failures in one infrastructure to propagate to other infrastructures, and are often the cause of widespread disruption, as in the 2003 blackout in the northeastern United States and southeastern Canada, and the disaster following Hurricane Katrina in 2005[1,2,11].

In their study, Buldyrev *et al.*[3] define a general theoretical framework for analysing the effect of system-wide interdependencies by studying the resilience of a system composed of two networks whose nodes are mutually dependent. To probe the functional integrity of the composite network, they use the number of nodes (size) of the 'giant component' of the system, the largest connected set of nodes. They study this quantity both analytically and numerically as a function of the progressive removal of network nodes, with each node removal simulating the failure of a specific network element. To do this they used the elegant framework of percolation theory, which concerns the connectivity properties of networks. In isolation, standard networks exhibit a critical threshold value for the fraction of nodes that can be removed above which the network becomes totally fragmented. On approaching this threshold the integrity of an individual network progressively decreases, and the giant component shrinks to zero at the critical threshold. In the case of interdependent networks, however, the authors find striking differences to this behaviour (Fig. 2).

In their model[3], the failure of nodes in one network can lead to the failure of nodes in a second network that in turn can cause the escalation of failures in the first network, ultimately leading to the disruption of the system. As a result, the value of the critical threshold is smaller than in an isolated network, indicating that a complete breakdown of the system will occur at a smaller level of sustained damage. More important, however, is the nature of the breakdown transition. In interdependent networks the fragmentation occurs with an abrupt 'first-order' transition, with the size of the giant component suddenly jumping from a finite value to zero at the transition point (Fig. 2). This makes complete system breakdown even more difficult to anticipate or control than in an isolated network.

Even more striking is the case of mutually dependent heterogeneous networks, where the degree distribution — the probability that each node in the system is connected to n neighbouring nodes — is 'heavy-tailed'. Buldyrev and co-workers[3] model this situation with two tightly coupled networks, each with power-law degree distributions, and find the reverse of the now-classic result that sees isolated heterogeneous networks as extremely resilient, with total fragmentation of the network occurring only when all the nodes of the network are damaged. By contrast, in interdependent networks total fragmentation is found above a finite and small fraction of failing nodes, and the more heterogeneous the networks the smaller the damage that can be sustained before functional integrity is totally compromised.

On the one hand, the results of Buldyrev *et al.*[3] offer a clear example of the complexities of and fragilities induced by network interdependencies. On the other hand, the percolation model is a very stylized model of networks' reactions to local damage, and therefore lacks

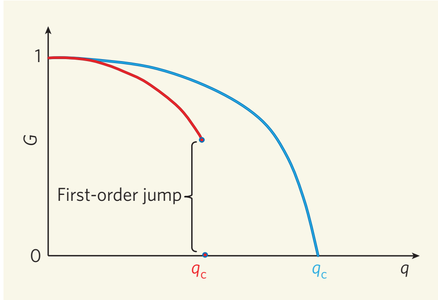

Figure 2 | Breakdown of isolated and interconnected networks. The quantity G is the largest number of connected nodes in a network, and is expressed as a fraction of the total number of network nodes; q is the fraction of nodes removed from a network and q_c is the critical fraction of nodes that on removal lead to a complete fragmentation of the network ($G = 0$). In isolated networks (blue curve), complete network fragmentation is approached continuously. Buldyrev and colleagues[3] show that in interdependent networks (red curve) it occurs abruptly ('first-order' transition) at a smaller value of q_c than in isolated networks.

the realism needed to capture many of the features that contribute to the resilience and robustness of real-world networks. After all, most physical and cyber interdependencies are defined by the flow of a physical quantity across the networks; the failure event and the network integrity are not just a connectivity problem. Nevertheless, Buldyrev and colleagues have set the scene for future research that will capitalize on these simple models by introducing higher levels of realism, and by simultaneously tackling engineering issues and globally emerging features in the analysis of infrastructure resilience. ■

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GENOMICS

Lessons in complexity from yeast

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A challenge in biology is to understand complex traits, which are influenced by many genetic variants. Studies in yeast provide the prospect of analysing such genetic variation in detail in other organisms, including humans.

Ever since the modern understanding of evolution and genetics in terms of natural selection and Mendelian inheritance was formulated, generations of scientists have struggled to explain the genetic bases and evolutionary significance of the remarkable variation among individuals, which is observed in many species. Despite considerable progress in finding the main genes that determine genetically simple traits, genetic variants of individually small effect that influence the so-called complex traits — which include height, weight and disorders such as neuropsychiatric diseases and cancers — have proved elusive. On page 1039 of this issue, Ehrenreich *et al.*[1] report a method in yeast that offers great statistical power for identifying multiple genomic regions that contribute to complex traits. Their work affords significant hope that similar genomic studies will be possible in many other species.

Over the past 20 years, various analytical and empirical approaches have been developed to find gene variants that influence complex traits[2,3]. One experimental technique, called bulk segregant analysis[4], examines progeny from crossing two different yeast strains and can potentially pinpoint multiple genes contributing to trait differences, especially when coupled with high-throughput analysis of the progeny's genotype[5]. More recently, these techniques have been merged with ways to select for progeny with extreme traits[6], thus allowing greater mapping precision and power. Ehrenreich and colleagues' paper now hints that we are finally poised for what may be a step change in our understanding of the genetic basis of organismal diversity.

The authors[1] report genetic variations in yeast that mediate 17 complex traits related to resisting chemicals. The main innovation here is to couple the generation of very large populations of progeny from an inter-strain cross