Predicting breakdowns of dynamical complex networks

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Large dynamical complex systems, such as animal communities, gut microbiota or the brain, can be modelled using networks in which components interact with their neighbors. The underlying structure of the networks are mostly responsible for the resilience to random natural fluctuations. For instance, food webs, which describe the predator-prey interactions, feature redundancy that maintains resilience to natural population fluctuations. But when the structure is damaged, the system stability is altered and a complete dynamical breakdown could occur. Close to the so-called tipping-points, networks are still remarkably resilient to fluctuations of the dynamical populations but extremely fragile to structure perturbations, which makes the imminent catastrophe almost undetectable to noninvasive approach. Moreover, large complex systems are often composed of billions of components, making them practically impossible to study using a direct approach.

Fortunately, large complex systems exhibit global behaviors. For instance, in the brain, large populations of neurons synchronize during specific tasks. Thus, complex networks are surprisingly well described by low dimensional formalisms. Constructing a low dimensional effective system is, however, a challenging task; it must represent the global features of the large complex system and provide relevant and correct predictions.

In this project, we have developed a dimension reduction formalism that satisfies all the above criteria. Large networks are first decomposed into dynamically independent, but non-exclusive, regions and are then reduced to smaller dynamical networks of few individuals. The resulting networks are constructed so that they model all the independent global behaviors of the original networks, with the advantage that they are interpretable and computationally tractable.

To predict breakdowns, structural network perturbations in a large system are transcribed into equivalent perturbations on the smaller structure, so we can measure the direct impact of perturbations on the global behavior. Moreover, we can predict accurately the impact of individual component removal. We analytically characterize the global bifurcation diagrams and quantify the resilience of the system to structural perturbations. The formalism has been shown to correctly predict catastrophes in all kinds of networks, including random, modular, and heterogeneous networks. It has also been successfully applied to theoretical dynamical models of very different nature, such as models describing the evolution of animal populations, the propagation of infectious diseases, and the activation of neural networks. Moreover, our work provides insights on the fundamental structural causes of complex network resilience and paves the way to design effective strategies of intervention for complex systems, particularly for those of the North that are highly stressed by environmental changes.