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Network Cascades: Unfolding, Modeling, and Control

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Abstract– A characteristic property of networks is their ability to propagate influences, such as infectious diseases, behavioral changes, and failures. An especially important class of such contagious dynamics is that of cascading processes. These processes include, for example, cascading failures in infrastructure systems, extinctions cascades in ecological networks, and information cascades in social systems. In this presentation, I will discuss recent progress and challenges associated with the modeling, prediction, detection, and control of cascades in networks. In particular, I will present new mathematical and computational models for cascading blackouts in power-grid networks that are both realistic and amenable to rigorous analysis.

1. Introduction

It is just a small exaggeration to say that we have reached the "network age." Now both more systems are recognized as networks—think of engineered materials, intracellular media, organismal physiology, ecological systems, swarming robots—and more networks have come into existence due to human activity—global financial and transportation networks; continental-wide power grids; the Internet; and large-scale social, communication, and information networks [1]. A characteristic property of networks is their ability to propagate influences, such as infectious diseases, behavioral changes, and failures. An especially important class of such contagious dynamics is that of cascading processes. These processes include, for example, cascading failures in infrastructure systems, where a network component may fail or disable itself in response to the failure of other components; extinctions cascades in food-web networks, where perturbation to the population of one species may cause a sequence of others to undergo extinction; and information cascades in social systems, where an individual's behavior is influenced by the behavior of others.

2. Distinctive Properties of Network Cascades

Cascading processes have intrinsic features that distinguish them from the simple contact processes that typically characterize other network-spreading phenomena like epidemic spreading and diffusion—which can be illustrated by comparing failures in a power grid with a model for the spread of flu in an unimmunized population of like individuals [2]. First, the likelihood of a node failing increases non-additively as a function of the number of other failures in the neighborhood, whereas in epidemic spreading the probability of acquiring the disease from a neighboring node does not depend on the state of other nodes. For example, a power station may never fail if only one connected station has failed, whereas an individual has a nonzero probability of contracting flu even if only one contact has the virus. Second, the propagation of cascading failures is not restricted to being local, in the sense that a power station may fail even if none of its close neighbors have failed, whereas in the epidemic case the virus can only reach an individual through a neighbor that is contaminated (assuming the network is the only medium for the transmission). Third, the impact of one power station failure on other individual stations can be disproportionally large compared to the average, whereas, all other factors being the same, the transmission probability is expected to vary little across different flu-infected individuals. Each of these properties, although illustrated here for cascading failures in power grids, also applies to most other cascading processes.

These differences have major implications. The *non-additivity* means that cascades can be more likely to propagate in networks with structures that allow reinforcement from multiple neighboring nodes (or connections), such as locally redundant networks despite their larger average node-to-node distance, whereas epidemics propagate more efficiently in networks with long-range connections, such as random ones. The success of viral marketing and information sharing through social media, for example, may depend critically on the interplay between network structure and the extent to which this property underlies the dynamics. The *non-locality* indicates that the state change of a node may remotely change the state of other nodes without changing the state of intermediate nodes, which has no analog in epidemics. This property has the potential to be more pronounced in networks with large average path length, such as power grids. The *disproportional impact* means that the influence of the change of state of a node depends not only on the connectivity pattern of the node—instead, the node itself may be more influential. The latter relates to the important issue of intrinsic fitness versus position in the network, which has implications for cascades as well as numerous other processes.

These distinctive properties have ramifications for the modeling, detection, and control of cascade dynamics [3]. Incidentally, while here I refer to nodes or connections, failure or adoption, etc. for concreteness, in the most general case a cascade can involve a variety of status changes in any or multiple types of network components.

3. New Cascade Models

Using power grid networks as model systems, here I will present two state-of-the-art models for the analysis, prediction, detection, and control of cascading failures.

Cascade events are easy to conceptualize but remain extraordinarily difficult to predict in practice. First, I will present a statistical framework that can predict cascade size distributions by incorporating two ingredients only [4]: the vulnerability of individual components and the co-susceptibility of groups of components (i.e., their tendency to fail together). I will show that correlations between component failures define structured and often surprisingly large groups of co-susceptible components. Because co-susceptibility is often a nonlocal effect, the results suggest that we may need nonlocal strategies for reducing the risk of cascading failures, which bears implications for future research.

Then, I will present a continuous model to describe cascading failures in power grids [5]. The model accounts for both the normal/failed status of the transmission lines *and* the synchronous/asynchronous dynamics of the generator nodes. In this framework, a cascade event is a phase-space transition from an equilibrium state with high energy to an equilibrium state with lower energy, which can be suitably described in closed form using a global Hamiltonian-like function. From this function, it can be shown that a perturbed system cannot always reach the equilibrium state predicted by quasi-steady-state cascade models, which would correspond to a reduced number of failures, and may instead undergo a larger cascade. In particular, I will show that, in the presence of two or more perturbations, the outcome depends strongly on the order and timing of the individual perturbations.

4. Final Remarks

These results offer new insights into the current understanding of cascading dynamics, with potential implications for real-time control interventions. Aside from their immediate implications for blackout studies, these results provide insights and a new modeling framework for understanding cascades in financial systems, food webs, and complex networks in general.

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