Scientists review worldwide rise of 'network of networks'

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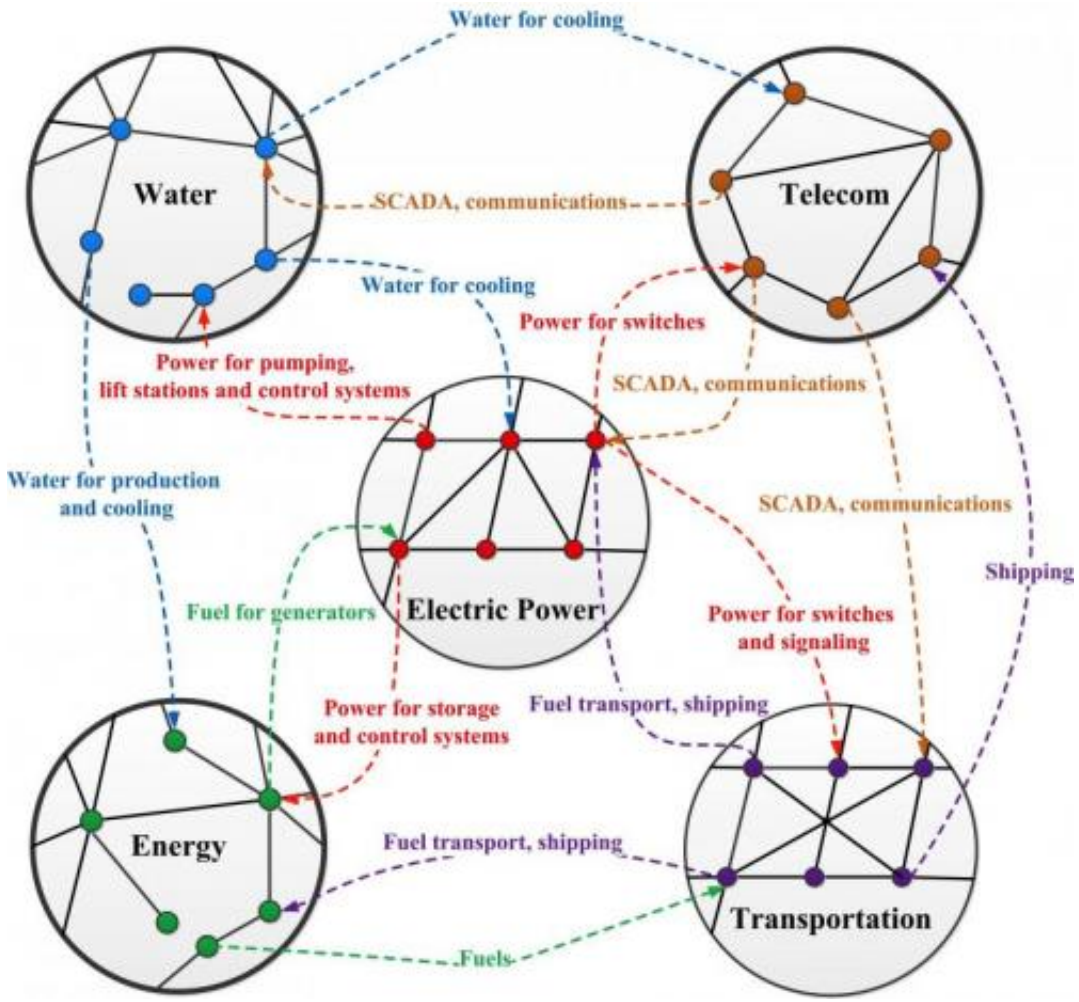

An illustration maps the interdependence of different infrastructure sectors. These complex relationships are characterized by multiple connections between infrastructure systems, feedback and feed-forward paths, and intricate, branching topologies. The connections create an intricate web that, depending on the characteristics of its linkages, can transmit shocks throughout broad swaths

of an economy and across multiple infrastructure systems. Credit: ©Science China Press

The interdisciplinary field of network science has attracted enormous attention in the past 10 years, although most results have been obtained by analyzing isolated networks. However many real-world networks interact with and depend on other networks.

"The properties and dynamics of interdependent and interconnected networks have been studied extensively, and scientists are finding many interesting results and discovering many surprising phenomena," state scientists based in China, the US and Israel who co-authored a new study, "From a single network to a network of networks," published in the Beijing-based journal *National Science Review*.

"Because most natural and engineered systems are composed of multiple subsystems and layers of connectivity, it is important to consider these features in order to improve our understanding of such complex systems," state coauthors Jianxi Gao, a scientist based at Northeastern University in Boston, Daqing Li, based at Beihang University in Beijing, and Shlomo Havlin, based at Bar-Ilan University in Ramat-Gan, Israel.

"Now the study of network of networks has become one of the important directions in network science," they point out in the *National Science Review*, in an issue of the journal specially focusing on network science.

The *National Science Review* is the leading English-language journal in China covering advances across the sciences.

Writing in the Review, the scientists state that a failure of a very small fraction of nodes in one network could lead to the complete

fragmentation of a system of several interdependent networks.

Networks of networks are common and diverse critical infrastructural systems are frequently coupled together, including water, food and fuel supply systems, along with communications, financial markets and power supplies (please see Figure 1).

Different systems in the human body, the brain, and the respiratory and cardiac systems regularly interact and are interdependent.

Social networks, including Facebook, Twitter and China's Weibo, play an important role in hundreds of millions of lives, and connect users to a globe-spanning system of interacting networks.

Deepening understanding of the network of networks is important for many disciplines and has real-world applications.

"Using percolation theory, we can study the robustness of a network and predict the critical percolation threshold, i.e. the fraction of removed nodes (or links) that leads to the collapse of the network," the three scientists state. "Furthermore, using percolation theory one can address some other issues, such as efficient attacks or immunization, for obtaining optimal path as well as for designing robust networks."

In interdependent networks, the coauthors note, "The failure of nodes in one network leads to the failure of dependent nodes in other networks, which in turn may cause further damage to the first network, leading to cascading failures and possible catastrophic consequences."

Many networks including transportation systems, power grids and even social networks are embedded in Euclidean space with spatial constraints.

"Spatial constraints not only manifest themselves in network vulnerability to random failures, but also make the system even more susceptible to spatially localized failures caused by natural disasters or malicious attacks," the coauthors report in the new study.

"Local failures, like the Tohoku earthquake and tsunami in 2011 or the recent typhoon in the Philippines," they state, "or a chemical/biological attack, can cause total failures within a given radius from the perturbation, which may propagate through the entire interdependent networks system."

The authors of the new study state they expect "the framework of interdependent network of networks to provide insights leading to further analysis of real data on interdependent networks."

"Further studies of interdependent networks," they add, "should focus on an analysis of real data from many different interdependent systems and the development of mathematical tools for studying real-world interdependent systems."

Study of this expanding and exciting field - the robustness of the network of networks - can be regarded as a new revolution in network science and will be essential reading for a wide range of physicists, mathematicians, computer scientists, biologists, engineers and social scientists.

More information: Jianxi Gao, Daqing Li, Shlomo Havlin , From a single network to a network of networks , *National Science Review* (September 2014) 1 (3): 346-356 , nsr.oxfordjournals.org/content/1/3/346.full

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