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EDITORIAL

# Focus on multilayer networks

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## Abstract
Multilayer networks have in recent years emerged as an important new paradigm of network science. Groundbreaking research has shown that processes that unfold on different but interdependent network layers can not be simply reduced to a conglomerate of additive processes on a single network. On the contrary, small and seemingly unimportant changes in one network layer can have far-reaching and indeed catastrophic consequences in other network layers. Such cascades of failures can lead to concurrent malfunctions in electrical power grids, they can gridlock traffic, and accelerate epidemics, to name just some examples. In the light of this functional relevance, network science has had to redefine structural measures, rethink growth processes, and come up with new mathematical formulations for multilayer networks. The field is still very much alight and vibrant, and with the focus on multilayer networks, the New Journal of Physics has given due space to the forefront research along these lines.

The past two decades have seen the coming of age of network science as a self-sufficient and independent research discipline, which at the same time has, perhaps like no other field of research, the potential to be seamlessly integrated, to enrich, and to synergize with other branches of science, from sociology and economy to biology, chemistry, and physics. The impetus for this fascinating development came with the discovery that seemingly diverse networks have universal properties that pervade across social, biological, and technological systems. In 1998, Watts and Strogatz [1] termed this the collective dynamics of 'small-world' networks, observing that electric power grids, food chains, brain networks, protein networks, transcriptional networks, and social networks are all highly clustered, like regular lattices, yet have small characteristic path lengths, like random graphs. Hence the name 'small-world' networks. Their simple and intuitive mathematical model was a hit, and although it yields a degree distribution that is unrealistic for most real-world networks, it was soon applied prolifically across the social and natural sciences. One year later, Barabási and Albert proposed the growth and preferential attachment model to describe the universal scaling in degree distributions of many realistic networks [2]. Their model, too, enjoyed—and still enjoys—fantastic popularity. The third major discovery came with the realization that many networks have groups of nodes that are much strongly interconnected with one another than they are to other nodes of the network, which today is well-known as community structure [3]. Combined, these and other breakthroughs propelled network science towards the top of the hottest fields of multidisciplinary research of the 21st century, as evidenced by several highly influential and cited reviews [4–7]. Physics, and in particular statistical physics and complexity, played a major role in the unfolding, emergence and establishment of modern network science.

Just as it looked like the pace of progress in network research might be starting to cool down, the Buldyrev *et al* [8] paper was published in 2010, reporting catastrophic cascade of failures in interdependent networks. The relevance of this seminal contribution lies in that it has pointed out in no uncertain terms the limitations of the field's focus on single, isolated, and non-interacting networks. The latter limitation is critical when it comes to analyzing real systems, given that modern economic, infrastructural, technological, as well as social and computer networks are coupled together and therefore should be best described as interdependent and multilayer networks. It was an important breakthrough, and while some argued that this is solely a matter of the viewpoint in that processes in different network layers could be added up and described as a conglomerate process on a single-layer network, it soon became clear that the challenge is by far not that simple. In the best tradition of complex systems, for multilayer networks too, the whole is not the same that the sum of its parts.

Indeed, further important discoveries followed fast, first with the generalization of network communities to multilayer networks [9], which allowed studies of community structure in more general settings including networks that evolve, have multiple types of links, as well as multiple scales. Subsequently, it was shown that even elementary physical processes like diffusion are fundamentally affected by multiplexity [10], and ultimately a mathematical formulation of multilayer networks was put forward [11]. Therein, the traditionally used adjacency matrices, which are useful to describe traditional single-layer networks, were replaced by a tensorial framework that allows the generalization of several important quantities and dynamical processes on multilayer networks, including degree centrality, clustering coefficients, eigenvector centrality, modularity, Von Neumann entropy, and diffusion. As previously for single-layer and isolated networks, popular and likewise highly cited reviews dedicated to temporal, multiplex, and multilayer networks attest to the vibrancy of this field of research [12–14], which has since found applications for better understanding epidemic spreading [15, 16], vaccination [17], evolution of cooperation [18], information cascades [19], and biological organization at different scales [20].

This fascinating development had not gone unnoticed at the New Journal of Physics, where the decision was made to host a focus issue dedicated to multilayer networks. Just little over a year after the first call for submissions was out, it is clear that the field is still beaming with outstanding research that addresses some of the most pressing societal and technological challenges of our time. In total, 23 papers have been published [21–43], covering subjects ranging from social contagion, interlayer competition, public cooperation, belief percolation, explosive synchronization, and epidemic spreading to cascading dynamics, consensus ranking, congestion, and meme spreading. Given the diversity of the topics that are covered by multilayer networks, it is challenging to pull a common thread through, and even to select, contributions that have been published in a brief editorial. Interested readers are therefore cordially invited to browse through the collection and discover for themselves the full breadth of research that has been covered and to select their favorite papers.

The future will certainly see further attention devoted to multilayer networks. We plan to present a perspective that will revise what are the most promising directions and future challenges in the field. The aims are to more accurately describe and understand collective social phenomena that are due to the interactions among individuals, groups, and governments, as well as to more efficiently tackle technological challenges that arise due to the interconnectedness of different components of information, computing, and transportation infrastructure. The hope is to ultimately develop better social systems, more efficient policies, and more resilient technologies for a sustainable future.

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