Introduction to Focus Issue: Mesoscales in Complex Networks

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Although the functioning of real complex networks is greatly determined by modularity, the majority of articles have focused, until recently, on either their local scale structure or their macroscopical properties. However, neither of these descriptions can adequately describe the important features that complex networks exhibit due to their organization in modules. This Focus Issue precisely presents the state of the art on the study of complex networks at that intermediate level. The reader will find out why this mesoscale level has become an important topic of research through the latest advances carried out to improve our understanding of the dynamical behavior of modular networks. The contributions presented here have been chosen to cover, from different viewpoints, the many open questions in the field as different aspects of community definition and detection algorithms, moduli overlapping, dynamics on modular networks, interplay between scales, and applications to biological, social, and technological fields.
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Over the past years, the bulk of the published work on complex networks has been restrained to either the local scale structure (through statistical distributions) or the macroscopic properties (with global parameters) of the network, but any of these two levels of description can apprehend the relevance of the intermediate modular scale typically present in biological, social, or technological systems. The collection of papers gathered in this Focus Issue is devoted to the hot topics related to mesoscale in complex networks. They are organized in six groups addressing questions regarding topological issues, dynamics on complex networks, and applications.

The complex networks discipline includes, indeed, a well-established theory and an increasing set of analysis tools through which the interactions among the elements of a graph can be represented and studied. Currently, such an approach has been fruitfully exploited in biology, technology, and sociology, and its advances have been compiled in a certain number of reviews, either in scientific journals and books.[1–3] When the field of complex networks started one decade ago, the interest focused on the taxonomy of real networks.[3] Later, the efforts progressively shifted toward more complicated issues, related to the role played by the networks in the real world. One field of research considered transportation and diffusion processes, motivated essentially for the application to epidemic processes. A second line was related to the analysis of the resilience against failures and attacks to networks, as well as problems concerning optimization in networked systems—both of great interest for technological networks. In this regard, the *Chaos* Focus Issue *Optimization in Networks*[4] nicely summarized the relevant work on this subject.

More recently, the fundamental question of considering network's nodes as having intrinsic dynamics (or, equivalently, an ensemble of dynamical systems being coupled through a nontrivial connectivity structure) has been the focus of much attention in the scientific community during the last years. This fruitful merging between complex networks and the well-established branch of dynamical systems has provided the right framework to tackle the relationship between structure and the emergence of a collective dynamical behavior. A good compilation of work on this topic can be found in the *Chaos* Focus Issue *Synchronization in Complex Networks*,[5] which is devoted to synchronization, one of the most important collective dynamics that can be found in complex networks.

Nowadays, a novel question is holding the attention of the researchers: the modularity of networks (and its dynamical/structural consequences). Since the seminal work by Girvan and Newman in 2002 on unveiling the modular network structure in social and biological networks,[6] it was evident that nature exhibits, in many cases, community structures (groups of highly interconnected nodes that are sparsely connected to the rest of the network). This modular organization has only been lately recognized to be crucial in the way in which a complex system works. For example, in metabolic networks, a community is related to all those chemical compounds involved in a specific function within the metabolism of a cell, or in social networks, it reflects social structure, and it can be related to opinion dynamics or rumor propagation. In the present Focus Issue devoted to networks mesoscale, we address the following questions in order to provide a full understanding of the subject:

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- *Definitions of mesoscales and communities in a complex network, methods for their identification and classifications*. In the literature, there exist several definitions of community based on concepts like betweenness centrality, *k*-clique percolation, spectral partition, hypergraphs, etc. At present, it is not clear if one of them will prevail or if some of them are equivalent through a still unknown relationship. Therefore, an interesting point is the establishment of a general and unambiguous mathematical definition of the concept of modularity. In this sense, the contribution from Granell *et al*.[7] show that there is no unique classification into mesoscales but, on the contrary, it is possible to define a hierarchy of communities depending on the affinity of nodes in order to synchronize with others. In addition, there is the issue of community detection. This is well known to be a nondeterministic polynomial time problem in graph partitioning and one of the most active fields in the study of complex networks. Therefore, even having the concept of community well defined, we still have the problem of designing efficient algorithms to detect and identify them. In this regard, Estrada[8] proposes a new series of methods of module detection based on communicability techniques that let us obtain higher modularity values than with the classical algorithms.
- *Coordination between mesoscales: Topological and functional overlapping between communities*. Community definition and detection is based on the idea that the set of communities is a full partition of the network (i.e., every node is assigned to one and only one community). In consequence, the majority of detection algorithms do not consider the possibility of community overlap. However, this approach is unavoidably missing information on how communities interact. For instance, in a metabolic network, a metabolite can be involved in more than one function or people usually belong to several clubs or groups in social networks. Consequently, the challenge is to introduce a proper framework for describing and detecting overlapping communities. A work addressing this question is the one presented by J. Hao *et al*.,[9] in which they introduce a useful approach, called "impact strength index", to measure the interaction between two groups, which takes into account both the heterogeneity and distance among them.
- *Growth and formation of mesoscales in a complex network*. Most of the existing models for network growth introduce modularity through topological arguments. Yet, very little attention has been paid to those mechanisms based on the dynamical behavior of the nodes, which are a common feature in many real systems. Then, the modeling of growing mechanisms able to provide a description of the "real" evolution processes involved in the formation of mesoscales is an absolute need. Gómez-Gardeñes *et al*.,[10] make an extensive study showing the differences in the route to synchronization between homogeneous and heterogeneous networks. They find that while in the former ones, a mesoscale of synchronized clusters with similar size emerges to finally collapse, in the latter ones, the transition is guided and centralized around the clusters containing the network hubs.
- *Dynamics on modular networks: The role of mesoscales and overlapping mesoscales in the production of a collective and coordinated dynamics*. It is evident that the existence of communities in a task-performing network is closely related to the coexistence of two (only apparently opposite) phenomena: the establishment of collective subtasks in the network (segregation of the graph) and the coordination of those subtasks at a global scale (integration). This hierarchical nature of the complex systems functioning is a feature not yet fully elucidated, and revisiting the issue of relating structure and dynamics of a graph at the level of the mesoscales is a major point. A first insight on this topic comes from Belykh and Hasler[11] who give a method to obtain the synchronous clusters from the topology in a synaptically coupled network of bursting neurons, showing how the mesoscale has different dynamical properties than that of the whole network.
- *Interplay between scales in complex networks and hierarchical organization*. Many recent works have contributed to establish the role that single nodes play inside the communities (acting as local hubs or being the connectors between communities). However, it is still an open question how certain nodes can influence the appearance, evolution, or interaction between communities, as well as explaining the correlation among the different scales of a network. A solution, given by Zhang *et al*.,[12] to evaluate the centrality of a node at different organization levels, such as hierarchy or modularity, consists in introducing a kernel function that quantifies the ranges of interactions of a node at various scales. Another interesting result related to the organization problem can be found in Corominas-Murtra *et al*.,[13] where they propose a definition of node hierarchy based on mutual information. In this way, it is possible to quantify how far the graph is from the ideally pure hierarchical tree structure.
- *Applications in biological, technological, and social networks*. Understanding the modular structure of a complex network may be a powerful approach to hot topics as neural networks, synthetic biology, navigation, or recommendation networks. One of the contributions to this Focus Issue deals precisely with the immune system. Madi *et al*.[14] present a new approach based on the construction of the network of mutual dependencies between antigens that can unveil important biological information within the context of the immune system, as the existence of conserved network motifs or modular reorganization of the networks between newborns and mothers. Other interesting application in the context of biological networks is the influence of a mesoscopic organization in the burst synchronization of a neuronal network. Sun *et al*.[15] find that two types of burst synchronization can be induced by the reorganization of the intra- and intercommunity couplings, a fact that could have strong implications in the plasticity of neuronal networks. Concerning technological applications, one has to mention the contribution by Yazdani and Jeffrey,[16] where they analyze a variety of strategies to understand the formation, structure, efficiency, and vulnerability of water distribution networks and critically evaluate practical applications of abstract complex network techniques. The approach used to

study the vulnerability of this kind of networks is particularly remarkable, since the connectivity between the components and water supply sources requires a different treatment from the conventional degree-based methods. In a different field, Stoop and Joller[17] project the semantics of the courtship dance of Drosophila into a network and use the mesoscale generated by the periodic orbit approach to analyze the complex language grammar of this behavior. Finally, Gómez-Gardeñes *et al.*[18] show that evolutionary games in social networks do not escape from the influence of a mesoscale organization. Apart from the well-known impact of the network degree or assortativity in the game dynamics, they show that the existence of communities in the interaction network enhances the cooperation between individuals of the same partition. Furthermore, the size of the community seems to be of special relevance: the larger the community, the lower the cooperation between individuals.

Although we believe that this Focus Issue on Mesoscales in Complex Networks sheds light on these six points, we think that it is even more important if it spurs more researchers on finding new proposals and methods or putting forward other questions that, involuntarily, we have omitted. This would be our major achievement.

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