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Scale-free systems organization as entropy competition

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Network structures are everywhere in nature, representing the unifying theme for understanding a number of very different phenomena across social, biological, technological, physical, hydrological and ecological systems. Such complex systems exhibit common behaviours as the scale invariance, for which the distribution of some properties of the constitutive elements follows a power-law (i.e. some system properties appear identical over a large range of scales). Moreover, these properties affect the dynamics of the system in a fundamental way: particularly, it has been demonstrated that the scale-invariance of complex networks implies their robustness under random deletion of elements. For example, in biology this explains the strong resilience exhibited by some simple organisms against gene removal. Analogously, in hydrology it is well know that network structure and specific system functions co-evolve with time, with strong interactions and feedbacks between patterns and processes at both catchment and fluvial scale. Consequently, a comprehensive understanding of the spatial and temporal patterns describing the network structures may be fundamental to many areas of earth sciences.

The basic characteristics of the network systems are not described by the nature of their constitutive elements, but rather by their topological properties (i.e. relations among the system elements). In this sense, the network theory provides an extremely useful approach. This theory schematizes an interconnected system by a graph, defined as a mathematical set of nodes (elements of the system) connected by edges (relations among the elements). The usefulness of the graph theory is in its universality. Indeed the node-edges schematization allows an effective descriptions for an extremely varied class of phenomena: social networks, as scientific collaboration networks, informatics systems, as the WEB and internet, biological systems, as protein-protein interactions networks and metabolic networks, technological systems, as electronic circuits, geomorphological systems, as river networks, and so on.

Here, based on statistical mechanics, we discuss how network systems organize themselves into an equilibrium scale-free structure. In particular, we show that the power-law is the most probable distribution that both nodes and edges, in a reciprocal competition, assume when the respective entropy functions reach their maxima, under mutual constraint. The proposed approach predicts scaling exponent values in agreement with those most frequently observed in nature.