Complex Networks in the Brain
– function vs. wiring and excitability

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ABSTRACT

This talk will describe recent work in our group in Granada [1] concerning the mathematical modeling of networked media which is of interest to better understanding brain dynamic properties including its functional and wiring structures. In particular, I plan to address some of the following issues.

The effects of varying wiring in networks of excitable units in which connection weights change with activity to mold local resistance or facilitation due to fatigue. Dynamic attractors are then destabilized, various nonequilibrium phases occur, including one in which the global activity shows chaotic hopping among the patterns, and strong correlations develop between topology and functionality. These correlations imply, in particular, that some brain tasks can be most efficiently performed on highly heterogeneous nets, and it also follows a possible explanation for the abundance in nature of scale-free network topologies.

An evolving network model in which the total numbers of nodes and edges are conserved, but in which edges are continuously rewired according to nonlinear preferential detachment and reattachment. Assuming power-law kernels with exponents α and σ, the stationary states which the degree distributions evolve toward exhibit a second-order phase transition —from relatively homogeneous to highly heterogeneous (with the emergence of star like structures) at $\alpha = \sigma$. Temporal evolution of the distribution in this critical regime follows a nonlinear diffusion equation, arriving at either pure or mixed power laws of exponents $-\alpha$ and $1-\alpha$.

¿Why most empirical networks are generically degree-degree anti-correlated? Defining a general class of degree-degree correlated networks, the maximum of the associated Shannon entropy may be shown not to typically correspond to uncorrelated networks, but to either correlated or anti-correlated ones. More specifically, for scale-free nets, the maximum entropy principle usually leads to anti-correlated, providing a parsimonious explanation to the question above. This approach provides a neutral model from which, in the absence of further knowledge regarding network evolution, one can obtain the expected value of correlations.

Models of excitable media in which nodes may occasionally be dormant and connection weights vary with activity on short--time scales. Their global activity happens to be quite unstable and sensitive to stimuli, which favors spontaneous occurrence of nonequilibrium phases and 1/f noise as the system is driven into the phase region depicting the most irregular and interesting behavior, namely, “states of attention” as in the brain. A net result is an efficient search in the attractors space that can explain the origin of some observed behavior, e.g., in neural systems. A previously conjectured relation between power-law distributions and a “critical state” concerning functionality of cortical networks is addressed, and the nature of such criticality in the model, which may guide experiments, is described in detail.

Weak signals may be efficiently transmitted throughout more than one frequency range in noisy excitable media by “stochastic multi-resonance”, recent experiments in neuroscience suggest. In fact, a model shows this behavior as a result of competition between (1) changes in the transmitted signals as if the units were varying their activation threshold, and (2) adaptive noise, namely, rapid activity--dependent fluctuations of the connection intensities. This is indeed known to occur in many

heterogeneously networked systems of excitable units in nature e.g., sets of brain neurons and synapses. It may find direct application in the design of sophisticated filters and other devices.

Heterogeneity of many networks in nature may arise via preferential attachment of some sort. However, the origin of other topological features, such as degree-degree correlations, is often not clear and attributed to specific functional requirements. To analyze this, a general scenario with simple biologically motivated assumptions is possible assuming that nodes gain or lose edges according to any nonlinear functions of local and/or global degree information. This explains very well data concerning both synaptic pruning in humans and the neural network of the worm Caenorhabditis Elegans. In particular, many nontrivial topological features of the worm's brain arise naturally at a critical point.

Short-term memory cannot in general be explained the way long-term memory can —i.e., as a gradual modification of synaptic conductance— since it takes place too quickly. On the other hand, known theories based on some form of cellular bi-stability do not seem to be able to account for the fact that noisy neurons are able collectively to store information in a robust manner. One may prove how a sufficiently clustered network of simple model neurons can be instantly induced into metastable states capable of retaining information for a short time. Cluster Reverberation, as it may be called it, could constitute a viable mechanism available to the brain for robust short-term memory with no need of synaptic learning. Relevant phenomena described by neurobiology and psychology, such as power-law statistics of forgetting avalanches, may be shown to emerge naturally from this mechanism.

Keywords: Modeling cooperative behavior, Networked excitable media, Brain structure and dynamics.

REFERENCES

[1] The bibliography in which the results reported here are published follows [2-8]. This also shows colleagues who collaborated in the project, namely, Sebastiano de Franciscis, Samuel Johnson, Jorge F. Mejías, Miguel A. Muñoz, and Joaquín J. Torres. Our work was supported by the Junta de Andalucía (FQM-01505), MICINN-FEDER (FIS2009-08451), and GENIL (CEB09-0010).

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