Modular Random Boolean Networks

Rodrigo Poblanno-Balp[1,2] and Carlos Gershenson[2,1]

[1] Centro de Ciencias de la Complejidad, C3, México
[2] Instituto de Investigaciones Matemáticas Aplicadas y en Sistemas, UNAM, México
balpeaux@gmail.com, cgg@unam.mx

Extended Abstract

Modularity plays an important role in evolution, for even unicellular organisms have separable functional systems (Wagner et al., 2007) which are relatively autonomous. Modularity allows for changes to occur within modules without propagating to other regions and the combination of modules to explore new functions (Espinoza-Soto and Wagner, 2010).

Random Boolean networks (RBNs) (Kauffman, 1993; Gershenson, 2004) have been a very popular model of genetic regulatory networks for several decades, where the state of N nodes is regulated by the state of K neighbour nodes using randomly generated Boolean lookup tables.

However, most studies consider homogeneous or normal topological connectivities between nodes. Aldana (2003) already studied the effect of a scale-free topology on the dynamics of RBNs. In this work, we study the effect of modularity on the dynamics of RBNs, which has been missing from most RBN studies, in spite of its prevalence in natural systems.

We define a modular RBN (MRBN) as a set of M modules connected by L "weak" links. Each module is a RBN with N nodes and K connections between the N nodes within the module. The total number of nodes N_{TOT} is given by $N \cdot M$, while the total number of connections T is given by $M \cdot (K \cdot N + L)$. The average connections per node K_{TOT} is $\frac{N_{\text{TOT}}}{T}$.

Our preliminary results suggest that, for a broad range of values of K_{TOT}, modularity induces complex dynamics, i.e. closer to the transition between the ordered and dynamic phases, also dubbed "the edge of chaos" (Kauffman, 1993). In terms of sensitivity to initial conditions, trajectories in the state space tend to converge in the ordered phase and to diverge in the chaotic phase. For regular RBNs, it is well known that the transition lies at $K = 2$ (Gershenson, 2004). At this point, trajectories neither converge nor diverge. This represents a balance where information can be stored (chaotic phase is too dynamic) as well as modified (ordered phase is too static). However, this behaviour is observed only in a small region of possibilities in unstructured, regular RBNs. Modularity broadens this region considerably, reducing the sensitivity to initial conditions for values of $K_{\text{TOT}} > 2$. Keeping N_{TOT} constant, the number of attractors grows as M grows, although the lengths of these attractors tend to decrease. The highest percentage of states in attractors is given when $N = M$.

We defend that modularity plays an important role in RBNs, as it constrains the topology in such a way that damage is not fully spread across the modular network. Thus, modularity reduces chaos and is desirable for evolvability. It is clear that there is a considerable dynamical difference between modular and regular topologies. Since most studies of RBNs have been made with regular topologies, their results have to be reconsidered in the light of the new evidence, given the fact that real genetic regulatory networks are modular (Segal et al., 2003; Callebaut and Rasskin-Gutman, 2005; Schlosser and Wagner, 2004).

References

Aldana, M. (2003). Boolean dynamics of networks with scale-free topology. *Physica D*, 185:45–66.

Callebaut, W. and Rasskin-Gutman, D. (2005). *Modularity: Understanding the Development and Evolution of Natural Complex Systems*. MIT Press.

Espinoza-Soto, C. and Wagner, A. (2010). Specialization can drive the evolution of modularity. *PLoS Computational Biology*, 6 issue 3.

Gershenson, C. (2004). Introduction to random Boolean networks. In Bedau, M., Husbands, P., Hutton, T., Kumar, S., and Suzuki, H., editors, *Workshop and Tutorial Proceedings, Ninth International Conference on the Simulation and Synthesis of Living Systems (ALife IX)*, pages 160–173, Boston, MA.

Kauffman, S. A. (1993). *The Origins of Order*. Oxford University Press.

Schlosser, G. and Wagner, G. P. (2004). *Modularity in Development and Evolution*. The University of Chicago Press.

Segal, E., Shapira, M., Regev, A., Pe'er, D., Botstein, D., Koller, D., and Friedman, N. (2003). Module networks: identifying regulatory modules and their condition-specific regulators from gene expression data. *Nature Genetics*, 34:166–176.

Wagner, G., Pavlicev, M., and Cheverud, J. M. (2007). The road to modularity. *Nature Reviews*, 8.