Guiding the Emergence of Structured Network Topologies: A Programmed Attachment Approach

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Emergent collective behavior, such as dynamic network self-organization, can result from the interactions between a multitude of agents driven by simple rules, a fact that is often touted as the hallmark of complex systems. However, a closer look reveals that in many well-known families of models (pattern formation, swarm intelligence, complex networks, etc.) "complexity" translates into emerging patterns that are either freely random, or determined by boundary conditions—or anywhere in-between. On the one hand, spots and stripes, meandering bird flocks, or hub-forming social encounters are fairly homogeneous or self-similar phenomena that can be described by *statistical* laws. They are typically stochastic, generating order from amplified fluctuations. On the other hand, the formation and stabilization of ant trails is constrained by landmarks such as the nest and food sources. Many other examples present a mix of internal homogeneity and external constraints.

Cases exhibiting an *intrinsic architecture* that is neither repetitive nor imposed by the environment are much less frequent or studied. One salient exception is the development of living organisms. Biological morphogenesis demonstrates the possibility of self-organized *and* elaborate structure formation. Segments and organs self-assemble in a decentralized fashion, arranging themselves in specific structures that resemble the products of human engineering design. This is because the agents (cells) carry a sophisticated set of rules (DNA) that endows them with a repertoire of non-trivial behaviors, and guide how they differentiate through various signals representing relative positional information.

There is great demand for such capabilities of guided self-assembly in many distributed computing systems, e.g., arrays of micro-processors, mobile sensors, internet security hosts, reconfigurable robot modules, or swarm robots. Such capabilities are also essential to the management and engineering of *complex techno-social networks* made of myriads of mobile devices, software agents and human users, all relying on local rules and peer-to-peer communication, e.g., the design of self-reconfiguring manufacturing plants, self-regulating energy grids, or self-deploying emergency taskforces.

We present preliminary results of an original model of autonomous network construction and dynamics, in which nodes execute the same program in parallel, however develop into different types according to their (limited) positional awareness. In our model, nodes exchange messages and dynamically create or remove links, based on "ports" and a set of internal state variables derived from discrete "gradients". Ports and gradients guide the new nodes to specific attachment locations in the network. As the network expands and node positions change, they adapt by switching different subsets of rules on or off—similar to gene activation/inhibition in biological DNA—thus triggering the growth of specific structures such as chains, lattices, and more complicated composite topologies.

Simple positive and negative-feedback rules are not sufficient in themselves to create elaborate architectures. Code-carrying nodes and programmed attachment could be the key to unraveling an "eNetwork DNA" that fosters *controllable* and *reproducible* self-organization in complex networks.