Architectures That Are Self-Organized and Complex: From Morphogenesis to Engineering

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Abstract— Self-organized physical systems generally form simple random patterns, while complicated, controlled architectures are generally the product of human design. So far, the only emergent (undesigned) *and* complex morphologies that we know come from biological development. Can we export their principles—multi-agent decentralization, self-repair, evolution—to our machines, networks and other artificial constructions? Can some future discipline of "*embryomorphic" engineering* solve the paradoxical challenge of planning autonomous systems? It is the goal of this work to better understand complex morphogenesis by investigating and combining its two fundamental ingredients, *self-assembly* and *pattern formation*. On the one hand, research in *self-assembly*, whether natural or artificial, has traditionally focused on pre-existing components endowed with fixed shapes. Biological development, by contrast, dynamically creates new cells that acquire selective adhesion properties through differentiation induced by their neighborhood. On the other hand, *pattern formation* phenomena are generally construed as orderly states of activity on top of a continuous 2-D or 3-D substrate. Yet, again, the spontaneous patterning of an organism into domains of gene expression arises within a multicellular medium in perpetual expansion and reshaping. Finally, both phenomena are often thought in terms of *stochastic* events—whether mixed components that randomly collide in self-assembly, or spots and stripes that crop up unpredictably from instabilities in pattern formation. Here too, these notions need significant revision if they are to be extended and applied to controlled morphogenesis. Biological cells are not randomly mixed but pre-positioned where cell division occurs. Genetic identity domains are not randomly distributed but highly regulated in number and position. In this work I present a computational model of *programmable* and *reproducible* artificial morphogenesis in a swarm of agents, inspired by biological development. It integrates self-assembly and pattern formation under the control of a nonrandom gene regulatory network. The specialized properties of agents (division, adhesion, migration) are determined by the gene expression domains to which they belong, while at the same time these domains further expand and segment into subdomains due to the self-assembly of specialized agents. This theoretical bio-inspired work could potentially lead to novel engineering applications—e.g., nanotechnologies (agent = microprocessor), distributed systems (agent = software), swarm robotics (agent = robot)—but also new conceptual tools for modeling and harnessing natural complex systems.