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The Growing Canvas of Biological Development: Multiscale Pattern Generation on an Expanding Lattice of Gene Regulatory Networks

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***Abstract*—** The spontaneous making of an entire organism from a single cell is the epitome of a self-organizing, decentralized complex system. Through a precise spatiotemporal interplay of genetic switches and chemical signaling, a detailed architecture is created without explicit blueprint or external intervention. Recent dramatic advances in the genetics of developmental biology, and its evolutionary version evo-devo, are bringing closer to reality the foundations of a future "generative developmental biology", which would unify the richness and endless diversity of biological forms as variations around a common theme. The variations are the specifics of the genetic code; the theme are the generic elementary laws by which this code produces the very proteins that further interpret it, controlling cell differentiation and morphogenesis. In this contribution I present a simple schematic model that simulates some of these developmental principles with growing cellular automata and coupled dynamical systems. An organism is represented by a network of networks, namely an expanding lattice of cells where each cell contains a genetic regulatory network (GRN) and interacts with neighboring GRNs via signaling molecules. A GRN is construed as a feed-forward multilayered hierarchy of logic switches that can settle in different states of on/off expressions. At every time step, local gradients of morphogen concentrations created by intercellular diffusion provide positional information to a cell via the input layers of its GRN. These spatial coordinates are integrated by propagation of activity through promoter and repressor links in the GRN, ultimately triggering the expression of specialized identity genes in the upper layers. Similarly to striping in the Drosophila embryo, the present lattice organism becomes segmented into spatial domains of homogeneous genetic expression. Meanwhile, it also expands by cell proliferation, creating new local gradients of positional information within former single-cell domains. These gradients activate in turn other entry points of each cell's GRN, producing refined patterns of cell identity at a smaller scale, etc. Thus, the alternance of phases of growth and patterning ultimately results in the creation of a "form", represented by an image or a shape on the lattice. Following Enrico Coen's artistic metaphor of a growing canvas that paints itself, my model attempts to reproduce pattern formation through a *multiscale generative process*. Starting with a few cells that express broad positional and identity domains, details are gradually added using only local information. Two questions are then of central interest in this framework: given the GRN weights, what pattern will the canvas create? Conversely, given a desired pattern as a target, what values should the GRN weights take to achieve this pattern? The first question is the missing genotype-phenotype link in biology's Modern Synthesis and main object of evo-devo. The second question addresses the technological challenge of dynamic self-assembly and autonomous design in the absence of a global symbolic blueprint, for example as in swarm robotics or distributed software agents. Previous artificial models of development have mainly followed the first, bottom-up approach, by observing and classifying (selecting) pattern emergence based on arbitrarily or biologically detailed GRNs. Here I also take the reverse, top-down approach and show that a given spatially-explicit blueprint can be implicitly encoded in the weights of a nonspatial GRN. In the same spirit as artificial neural networks or ant colony optimization, my goal is less a faithful reproduction of biological mechanisms than their abstraction and potential application to computational problems. Drawing from biological development, I hope to be contributing to a novel engineering paradigm that would replace omniscient architects with decentralized collectivities of agents.