Robust Engineering Using Biologically-Inspired Models of Cell Differentiation and Morphogenesis

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The Problem: In this research, we propose to use morphogenesis and developmental biology as a source of algorithms and general principles for organizing complex behavior from locally interacting individuals. We aim to design artificial systems that replicate biological robustness, and to use insights from these systems to understand the capabilities of biological systems. The goal is to be able to formalize these general principles as programming languages — with explicit primitives, means of combination, and means of abstraction — thus providing a framework for the design and analysis of self-assembling systems.

Motivation: Within the next decade, emerging technologies will make possible novel applications that integrate computation into the environment: smart materials, self-reconfiguring robots, self-assembling nanostructures. We are faced with the challenge of achieving coherent and robust behavior from the interactions of multitudes of elements and their interactions with the environment. These new environments fundamentally stress the limits of our current engineering and programming techniques, which depend on precision parts and strongly regulated environments to achieve fault-tolerance. By contrast, the precision and reliability of embryogenesis, in the face of unreliable cells, variations in cell numbers, and changes in the environment, is enough to make any engineer green with envy. We believe that important organizational lessons can be learned from natural biological systems.

Previous Work: Nagpal has demonstrated the power of the programming-language approach by developing a system for programmable self-assembly [2]. The system combines local primitives from epithelial cell morphogenesis and *Drosophila* cell differentiation, with combination rules from the mathematics of paper folding. The language specifies a folding process on a flexible sheet composed of many identically-programmed agents or "cells". The specification describes a global process that is *automatically compiled* into local programs that are run on the individual cells. The process is extremely reliable in the face of random cell death, random cell distributions, and varying cell numbers. The language is also *scale-independent* in that the resulting shape scales according to the size and proportion of the initial sheet without changes to the program. This work is part of a larger vision, called Amorphous Computing [1], where the goal is to develop new paradigms for acheiving predetermined, robust, global behavior from the cooperation of large numbers of unreliable parts that are interconnected in unknown, irregular, and time-varying ways. Several other programming languages have been developed under this program and are described in a separate abstract.

Approach: The goal of this research is twofold: to extend our programming models to new domains, and to investigate the connection of our models to biological processes.

We will design new languages that describe the formation of shape by exploiting replication (growth), motility, and deletion (cell death). Just as paper folding is a natural process for shape formation on a sheet, we will need to discover new models to describe shape formation in these new domains.

Our previous work has exhibited several similar traits to biological systems and provided us with insights into how these systems may work. We will exploit these insights to design biological experiments, and intend to collaborate with biologists to perform these experiments. Specifically, we plan to investigate scale independence and morphological differences in closely-related species. We will also investigate the connection between the kinds of failures that we have observed in the simulated morphogenesis processes and those that occur in naturally-occurring birth defects, concentrating on failures of geometry, topology and synchronization.

Impact: The results from this research will have significant impact, not only on our engineering principles for robust design but also on our understanding of biological systems. These new programming models will impact

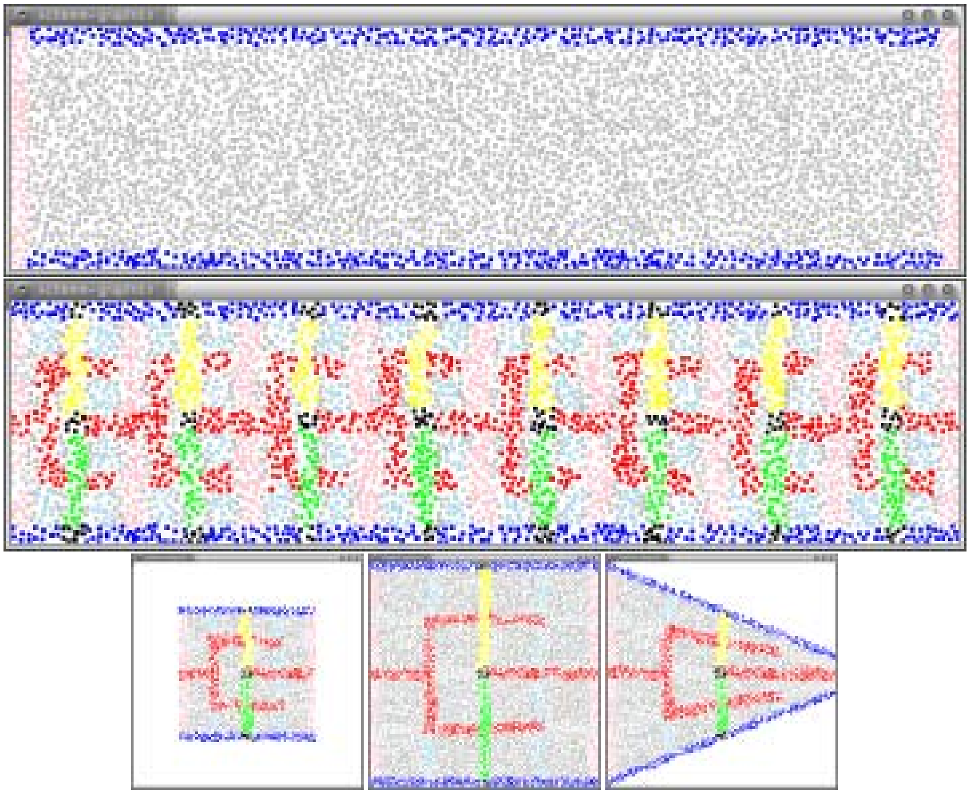

Figure 1: The figure shows a sheet of identically-programmed and locally-interacting elements differentiating into an inverter chain pattern. Initially only the elements on the border have special state. The desired global pattern is described abstractly on a continuous sheet, using a language based on paper-folding (origami) axioms. The program run on an individual element is automatically generated from this abstract description. The global description also includes a degree of modularity, for instance the inverter chain is composed of repetitions of a simple inverter pattern. The program also scales, *without modification*, as the size (number of elements) or shape of the sheet changes. The same language can be used to describe shapes created by folding a sheet of cells, and the modularity and scaling concepts apply to shape formation as well.

the design of and approach to reconfigurable robotics, self assembly, and smart-matter applications. In the long run we believe these ideas will help achieve coherent behavior from aggregates of biological cells. The biological comparisons will significantly improve our understanding of development and creation of morphology and hopefully promote the use of computational models for understanding systems-level biology.

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References:

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