

Research Statement

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My research interest is developing programming paradigms for robust collective behavior, inspired by biology. Cells with identical DNA cooperate to form complex structures, such as ourselves, with incredible reliability in the face of constantly dying and replacing parts. Emerging technologies are making it possible to bulk-manufacture and embed millions of tiny computing and sensing agents into materials and the environment. We would like to build novel applications from these technologies, like smart materials and self-reconfiguring robots, that achieve the kind of complexity and reliability that biological systems achieve. This requires solving two problems:

- How do we take a high-level description of global cooperative goals and translate it into local instructions for identically-programmed agents?
- How do we achieve robust and predictable behavior from vast numbers of unreliable parts?

I am interested in using morphogenesis and developmental biology as a source of algorithms and general principles for organizing complex behavior from locally interacting individuals. My approach is 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.

My PhD dissertation is an example of using this approach for shape formation on an intelligent reconfigurable surface composed of thousands of identically-programmed agents. I developed a programming language for specifying the desired global shape at an “abstract” level, as a folding construction on a continuous sheet of paper, which is then *automatically compiled* to produce the program run by an agent. All agent behavior is constructed from a set of five robust local primitives, inspired by epithelial cell morphogenesis and cell differentiation in multicellular organisms such as the *Drosophila*. The global-to-local compilation is achieved by composing these primitives in a principled way, using a set of geometry axioms taken from paper-folding mathematics. The resulting process is versatile and reliable in the face of random agent distributions, varying numbers of agents and random agent death, without relying on global coordinates, a global clock, or centralized control. I provide a theoretical analysis of the robustness of the system. The system also exhibits *scale-independence* — the proportions of the shape scale automatically to the number of agents, without any modification to the agent program.

The power of the programming language approach is that it allows us to take advantage of traditional computer science techniques for managing complexity, while relying on biological models for achieving robustness at the local level. The compilation process makes it possible to easily specify complex behavior from thousands of identically-programmed agents. This programming methodology can impact emerging fields such as reconfigurable robots, smart matter, and self-assembling systems, where we are trying to program specific global structure and function from vast numbers of parts.

After completing my PhD, I wrote and received a grant from NSF to extend this programming paradigm to new domains and investigate mechanisms from developmental biology based on cell growth, programmed death and mobility. In the past year and a half I have been working with several graduate and undergraduate students on projects towards this goal:

1. We have recently applied programmable self-assembly to a new domain: the synthesis of arbitrary 3D volumetric shapes, inspired by cell growth in biology. We can compile a graphical description of a global shape to produce a program for a single agent that then “grows” the structure through replication. The compilation process borrows simple decomposition techniques from computer graphics, while the local agent behavior reuses the biologically-inspired primitives developed in my thesis,

along with a new primitive based on cell competition. The system exhibits many of the same robustness and scale-independence properties. I plan to apply this programming model to self-assembling robots, replacing cell growth and death with mobile agents that selectively attach and detach.

2. We are investigating primitives for self-repair inspired by healing in biology, specifically regeneration in the cockroach and starfish. For example, we have developed a primitive for creating self-repairing topological patterns on a 2D surface of agents. If regions of agents are destroyed then the pattern automatically reorganizes around the fault to preserve the original connectivity. The self-repairing capability is a side-effect of the pattern formation process and occurs without explicit monitoring of faults. I plan to develop a catalog of self-repairing primitives that maintain geometric, topological and functional constraints.
3. Many of the concepts for robust collective behavior developed in my thesis have direct applications to sensor networks and smart materials. Prior to my thesis, I designed several decentralized algorithms for leader-election, hierarchical group formation, coordinate system formation, and ad-hoc routing. Recently many of these algorithms have been implemented on the Berkeley sensor motes by Dr. Howard Shrobe's group at MIT. The key characteristic of these algorithms is that they do not rely on specific network topologies, perfect reliability, access to global position, or synchronous behavior. I am currently collaborating with them on the design of self-maintaining global coordinate systems and time synchronization for wireless sensor networks, based on primitives developed in my thesis.
4. Over the past year, I have been investigating applications of models of scale-independence from my dissertation to specific examples in developmental biology, in collaboration with Prof. Frankel from the Biological Sciences Department at the University of Iowa, and more recently Dr. Gunawardena at the Bauer Center for Genomic Research at Harvard. Two specific cases I am studying are: scaling in early *Drosophila* segmentation, and asymmetric scaling in morphologically-divergent but closely-related species of Hawaiian *Drosophila*. This work is in the early stages, but in the long-run this research can provide a methodology for studying properties, and failures, that emerge at the multicellular level with little to no change in DNA.

Biology gets tremendous mileage by using vast numbers of cheap and unreliable components to achieve complex goals reliably. Developmental biology can teach us how to make complex shapes, with well-defined topological and functional structure. Study of social insects can teach us how to program self-assembling and distributed robots. I intend to continue to design engineering languages for artificial systems that replicate biological robustness, as well as use insights from these systems to understand the capabilities of biological systems.