Programmable Materials

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Motivation: Rather than build precisely engineered mechanical structures, one could imagine programming precise complicated structures on a flexible mechanical base. Not only could one design many complex static structures from a single substrate, but also produce dynamic structures that can react to, and affect, the environment. Such a programmable material would make possible a host of novel applications that blur the boundary between computation and the environment.

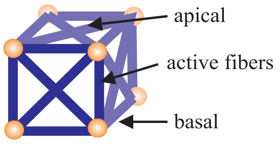
Example applications might be a flexible car surface that can change structure exactly at the point of impact, rather than having specifically engineered crumple points; an airplane wing that can dynamically change shape to resist shear; a programmable assembly line that can move objects around by producing ripples in specific directions; a reconfigurable robot that can change its shape to match different functions; or a manufacturing line that replaces precise mechanical engineering with programming.

Previous Work: Biology, in particular morphogenesis, gives us many examples of complex physical structures formed from the cooperation of large numbers of cells. One example is epithelial cell sheets that can organize into complex structures, such as branching tubes and neural folds, through the actuation of many individual epithelial cells - even though each cell has limited force. Odell, Oster, Alberch, and Burnside [2] present a mechanical model for how embryos form structures during development through the local deformations of epithelial cells. A cell is modeled as a rectangle made of fibers that contains an incompressible fluid. Apical (top) fibers can actively contract and cause what is known as a *purse string contraction*. Invaginations in the embryo occur when several connected neighboring cells contract. By varying the characteristics of the fibers, the authors model invaginations similar to those seen during gastrulation, neurulation and ventral furrow formation.

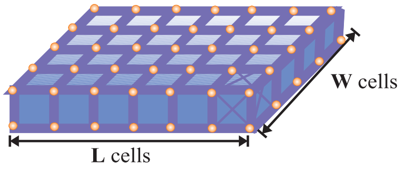
Approach: The objective of this research is to demonstrate the feasibility of programmable materials by providing a mechanical model for a programmable material and a programming paradigm for engineering global shape change. The approach is based on the behavior of epithlial cell sheets.

A Structure Composed of Active Cells: The key insight from the work by Odell *et al* [2] is the use of a *simple mechanical cell* that can actively deform its own shape and sense deformations in its shape. Such a cell could form the basic element of a more general programmable material.

Active Cell



Cell Sheet



The *Active Cell* can sense local stress and apply local force through program-controlled fibers embedded in its membrane. The fibers act like damped springs and can actively contract or expand by changing their rest lengths. By programming the active fibers, one can create many simple shape changes - long columnar cells, short fat cells, triangular or conical cells (figure 1).

The active cells can be connected together to form various flexible substrates which can then be programmed to form different global structures. Figure 1 presents some shapes formed by active cells connected in a ring. Many of these shapes are biologically inspired - such as invaginations, bulbs, a cell cleaving into two and folds forming on the cornea. Practically any shape can be formed given the limitation of the number of cells and the ring configuration. A more

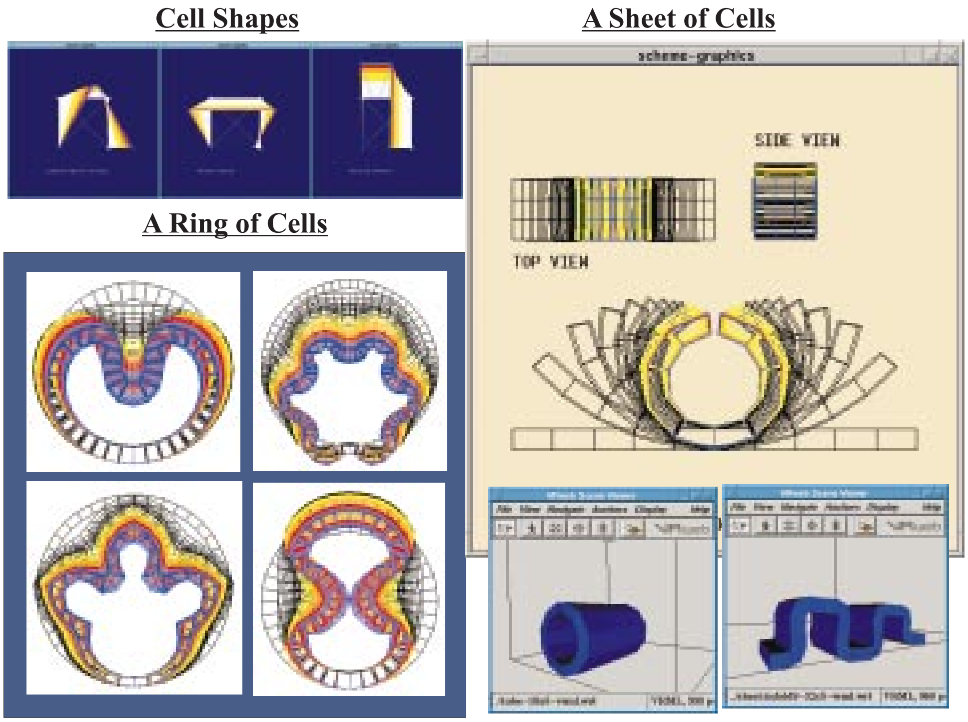


Figure 1: Programmable Materials Simulations

interesting substrate is a sheet of cells that can form different shapes such as folds and tubes. These shapes can then be combined to generate more complex behavior, such as dynamic ripples that move an object along the sheet.

Programming Paradigms: Technologies such as microfabrication and microelectronic mechanical devices (MeMs) are already making it possible to bulk manufacture and embed tiny computing elements integrated with microsensors and microactuators into materials and fabrics. Fabrication, however, is only one part of the story. An important question that still remains is how one programs global behavior from the local interactions of large numbers of identically programmed elements, where each element has limited resources, limited reliability and only local information and impact. Addressing this question has been a primary goal of the amorphous computing project [1], which forms the context for this research.

The current simulations suggest that a wide variety of global shapes can be achieved as compositions of a few simple local cell shape changes. By combining this with simple pattern formation techniques (chemical tropisms, coordinate systems, etc) from amorphous computing, one can conceive of programming the cells to coordinate to form the desired mechanical pattern. The ultimate goal is to develop a programming language - with primitives, means of combination and abstraction - for engineering global shape change on structures of identically programmed cells, using only local communication, local sensing and local actuation.

Impact: A programmable material would make possible a host of novel applications that blur the boundary between computation and the environment, expanding the horizons of traditional computer science.

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References:

[1] H. Abelson, D. Allen, D. Coore, C. Hanson, G. Homsy, T. Knight, R. Nagpal, E. Rauch, G. Sussman and R. Weiss. Amorphous Computing. *White paper*, 1999.

[2] G.M. Odell, G. Oster, P.Alberch, and B. Burnside. The Mechanical Basis of Morphogenesis, 1. Epithelial Folding and Invagination *Developmental Biology, vol 85*, 1981.