Amorphous and Cellular Computing

Hal Abelson, Don Allen, David Christman, Daniel Coore, Chris Hanson, Tom Knight, Radhika Nagpal, Erik Rauch, Gerald Jay Sussman, Chris Terman, Pater Thompson & Ron Weiss

Artificial Intelligence Laboratory
Massachusetts Institue Of Technology
Cambridge, Massachusetts 02139

http://www.ai.mit.edu

The Problem: A colony of cells cooperates to form a multicellular organism under the direction of a genetic program shared by the members of the colony. A swarm of bees cooperate to form a coherent hive. Humans group together to form towns, cities, and nations. These examples raise fundamental questions for the organization of computing systems: How do we obtain coherent behavior from the cooperation of large numbers of unreliable parts that are interconnected in unknown, irregular, and time-variable ways? What are the methods for instructing myriads of programmable entities to cooperate to achieve particular goals? These questions have been recognized as fundamental for generations. We argue that now is an opportune time to tackle the engineering of emergent order: to identify the engineering principles and languages that can be used to observe, control, organize, and exploit the behavior of programmable materials.

Motivation: The new impetus for the study of amorphous computing is inspired by the recent astonishing developments in fundamental biology and in microfabrication. Each of these is the basis of a kernel technology which makes it possible to build huge numbers of almost-identical information-processing units, (with actuators and sensors) at almost no cost. However, to exploit the potential of these technologies will require new insights into programming and system organization.

Microelectronic components are so inexpensive that we can imagine mixing them into materials to be produced in bulk, such as paints, gels, and concrete. Engineers can use such smart materials to replace or augment strength and precision in mechanical and electrical apparatus by the application of computational intelligence. For example, we imagine coating a building or a bridge with ”smart paint” that reports on traffic loads, wind loads, and monitors the integrity of the structure.

Previous Work: There are existing technologies (such as flexible printed circuits) that permit arranging microcomponents into pre-specified patterns. However, to fully exploit the potential of intelligent materials, it will be essential to obtain the desired behavior without the need to precisely fabricate the interconnect of the microelectronic components, and without the expectation that all the components are operational or that they are arranged as planned.

Approach: Biological organisms, of course, accomplish just the kind of organized behavior of amorphous systems that we wish to engineer. But it is only just now that biologists are learning the precise structure of complete organisms: the July 1995 issue of Science printed the complete genome for a bacterium, and hundreds more complete organisms will be sequenced over the next few years. We will thus be in the position of knowing the complete “microcode” for organisms, the effect of most of the genes, and we will even have at hand the technology to assemble such “programs”. However, we do not have programming paradigms and methodologies that help us to exploit biological mechanisms as an engineering technology for fabricating intelligent materials.

We can expect to find some clues in developmental biology. Recent advances in understanding the developmental process in complex biological systems, notably Drosophila, are uncovering the organizing principles used to differentiate and organize organs and organ groups within such systems. We can learn much from living things’ ability to dynamically organize arrays of initially identical cells into highly ordered arrays of differentiated organs and to interconnect these systems in organized ways.

We are also investigating prototypes, both in traditional silicon technology and in molecular biology. We have demonstrated, by simulation of reaction kinetics, the theoretical feasibility of building a family of logic gates where the signals are represented by concentrations of DNA-binding proteins, and where the nonlinear amplification is implemented by in vivo DNA-directed protein synthesis. We have completed the first phase of installing and equipping

Figure 1: The amorphous computing wall with approximately 50 prototype elements.

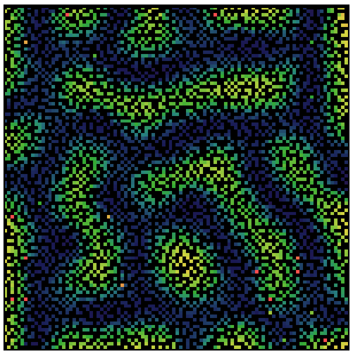

Figure 2: An amorphous simulation of reaction and diffusion of chemical species using the Gray Scott equations.

of a complete recombinant DNA laboratory for constructing and characterizing “cellular logic” gates, based on these theoretical foundations. We will use this laboratory to construct novel organisms incorporating small digital circuits.

Difficulty: All these visions of intelligent materials present the same fundamental challenge: To obtain desired, coherent behavior from large numbers of unreliable parts that are interconnected in unknown, irregular, and time-varying ways, by deliberately orchestrating their individual behavior and their cooperation. But in an amorphous computer the details of the interconnect are unknown and possibly variable since individual elements may be unreliable, or even mobile! Because there may not be a consistent way to assign coordinates to all of the computing elements, most tasks must be formulated in a coordinate-free way. Amorphous machines cannot rely on global synchronization, globally identified physical elements, or even elements that persist for the duration of the computation.

Traditional ways of formulating computational tasks make almost no effort to relate the approximate geometry of the problem to the approximate geometry of the computing mechanism. To tie the geometry of the problem closely to the geometry of the computer we are forced to confront this relationship head on. However, unlike work in cellular automata, we cannot depend on the details of the geometry of the computer, and unlike work with supercomputers and massively-parallel systems we will not be concerned with the particular patterns of referencing memory or allocating particular operations to well-defined arrays of computational units.

Impact: Beyond its immediate applications to programmable materials, the study of amorphous computing has fundamental implications for software design in general. Our ability to program complex software systems is not keeping up with our desire to solve complex problems. Nor has it matched the growth in computational resources that are available to help in the solution. We have, in too many cases, made Faustian bargains in software system design: attaining efficiency by reducing the number of computing operations required, but at the sacrifice of simplicity and understandability. It once made sense to attempt to eke out performance from computers by any technique that could reduce operation counts. As systems become more capable, however, the dominant costs are measured not in terms of operation counts, but in terms of the conceptual simplicity of code and the required communication between concurrent tasks. One effect of studying amorphous computing is that it forces us to reassess the cost, now perhaps poorly justified, of making algorithms non-local and inherently complex in order to reduce operation counts.

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