Information Mechanics Group

Research Staff

Norman Margolus
Tommaso Toffoli (group leader)

Graduate Students

Raissa D'Souza
Mark Smith

Postdoctoral Fellow

Mike Biafore

Visiting Scientists

Bruce Boghosian
Jeffrey Yepez
Pierluigi Pierini

Research Affiliate

Dan Rothman

Research Programmer

Harris Gilliam

Undergrad Students

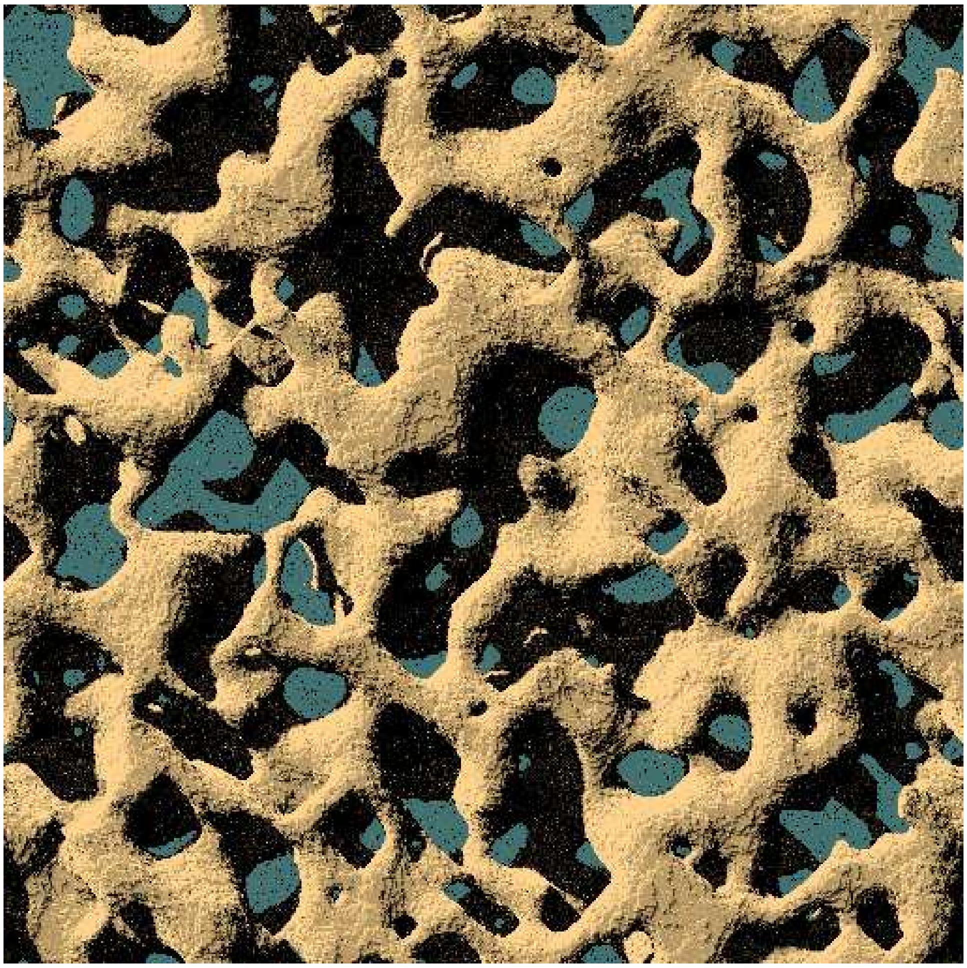
Chris Adler
Reuben Agin
Rebecca Frankel
Surya Ganguli
Jason Quick
Daniel Risacher

Support Staff

Joanne Talbot

Progress Report

1993–94



3-D Ising model, below the critical temperature

MIT Laboratory for Computer Science
Cambridge, MA 02139

This has been a very productive year for the Information Mechanics group. In addition to a number of outside collaborations, we have also been collaborating with several groups within MIT and are in the process of setting up additional MIT collaborations (we have funding for 6 RA's for groups that want to collaborate with us); we have graduated 2 Physics Ph.D.'s; we have made substantial theoretical progress in our cellular automata (CA) research; our quantum-scale computation research is becoming more exciting because of recent theoretical progress in that area; and we have started a new seminar series to increase awareness at MIT about the Physics of Computation.

1 CA research

CAM-8 continues to be the rallying point for our CA research. The object of the CAM-8 hardware project was to produce machines that are well suited to spatially organized, local, non-numerical calculations such as lattice-gas simulations of physical systems. We took a virtual-fine-grained approach, with emphasis on scalability, cost/performance, and visualization/analysis capabilities. The result was that in our small-scale prototypes, we take an amount and kind of hardware comparable to what you might find in a high-end personal computer, and arrange it into a personal CA supercomputer. These small prototypes run typical lattice-gas simulations at a speed and on a scale comparable to the best simulations that have been done on any machine.

Our small prototypes have been running for about 2 years now, and we have several of them out in the field (with collaborators who've paid for them), with another half dozen slated to go out to various research groups in the U.S., Canada, Europe, and Asia in the next few weeks (including one to the Media Lab).

1.1 Collaborations

Our closest collaborator remains the U.S. Air Force. They have two of our machines, and would like another five as soon as we're able to arrange for it. Jeff Yepez and his group there have used CAM-8 to make a number of breakthroughs in lattice-gas modeling, including momentum conserving models of liquid/gas phase transitions, and the first lattice gas models of elastic solids (Fig. 1). They are trying to arrange to have their new large CAM-8 machine built by Lincoln Labs, with us overseeing this project. (The Air Force Initiative for building a large CAM-8 machine started about a year ago).

Our collaborators at the University of Wisconsin are making their CAM-8 the basis of what they call the "Eco-machine" project—a suite of software they are developing to make the CAM-8 machine useful to a large modeling community. This project was based at least partly on the fact that their reaction-diffusion models ran about 17,000 times faster on CAM-8 than on their workstations.

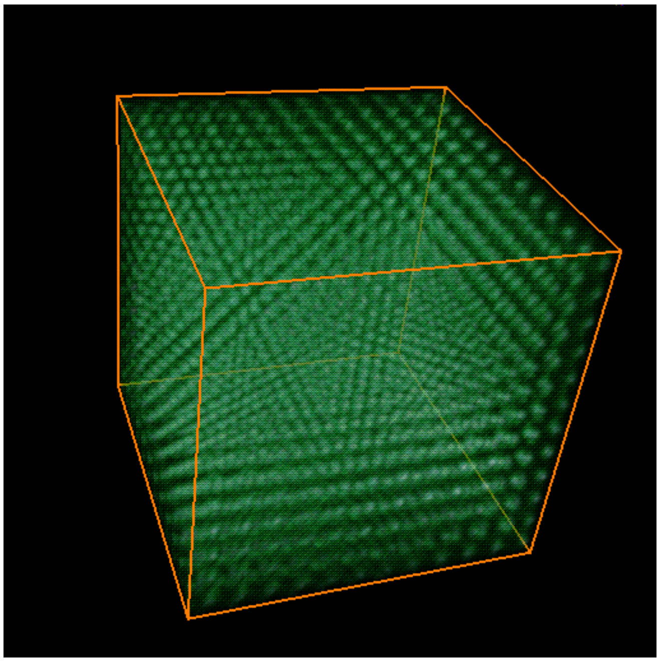


Figure 1: Modeling of interatomic forces; CAM-8 simulation on $512\times512\times512$ ($\approx 1/8$ billion) sites.

Several collaborators, including Joel Yellin at U.C. Santa Cruz and Bryant York at Northeastern, have been using CAM-8 for combinatorics calculations (adjacency-matrix calculations, jamming densities, etc.). We're just beginning to collaborate with mathematicians at MIT on these kinds of simulations (we recently helped Peter McCorquodale implement a CAM-8 version of a combinatorial dynamics due to James Propp in the MIT Math Department).

We've also begun setting up a collaboration with MGH (through Tuan Cao-Huu) to study the use of CAM-8 in analyzing PET scan data. The volume rendering techniques that we've developed to visualize physical systems in three dimensions (see title page) should work well in this context; and our machine should be very effective for CA-based image-segmentation algorithms.

Dan Rothman, Eirik Flekkoy, John Olson and Chris Adler (all at MIT-EAPS), have adapted a CM-2 algorithm due to Bruce Boghosian (Thinking Machines Corporation) to simulate 3-D lattice-gas fluids much more efficiently on CAM-8 than the original algorithm did on the CM-2.

In order to promote collaborations, CA modeling in general, and our approach in particular, CAM-8 has trav-

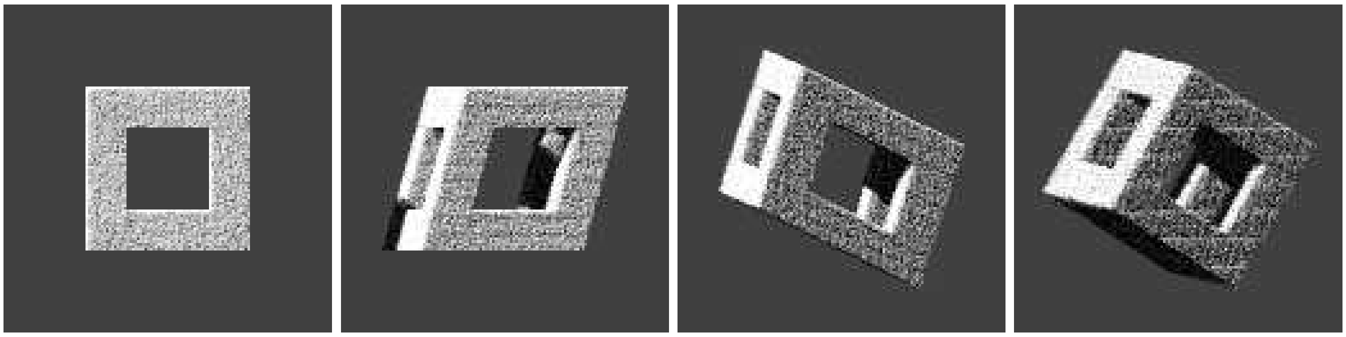


Figure 2: Three-dimensional rotation achieved by three shears.

eled extensively this year. The farthest its been was last September, when it was featured at the Second International Conference on Theoretical Physics in Beijing, China. It was presented at the lattice gas conference in Toronto last year, and will be featured in several talks at this year's meeting in Princeton, at the end of June.

1.2 CA algorithms

One of our own most interesting new CA algorithms is a new technique for rotating three-dimensional bit-map data (Fig. 2). This is particularly effective on CAM-8 since the basic operation is a *shear*, which this machine can implement very efficiently.

Our CAM-8 prototype has provisions for direct camera input. An example of realtime image processing performed with CAM-8 is shown in Fig. 3. The left half of the image reflects raw data coming from the camera, the right half has been subjected to an entropy-maximizing re-binning of the pixel values in order to improve image contrast. Our small prototype can do a significant amount of image processing in real-time: it can perform about 1600 updates per second of a 512×512 image, with an arbitrarily chosen lookup-table algorithm and complex spatial data reshuffling at every update.

Another interesting new algorithm is a generalization of our wavefront-volume-rendering algorithm. The image on the title page is a simple example of the kind of CA volume rendering that we've been doing since 1988 (cf. our CAM-8 flipbook). It was produced on CAM-8 in real-time: while a 3-D Ising dynamics governs the evolution of the matter, we continuously produce and display rendered images without appreciably slowing down our simulation. Each rendered image is constructed by sweeping a wavefront of "light" down through the sytem, as the processors sweep through to perform a single update of the matter. A second sweep brings reflected light forward, again while the matter is updated, and the resulting 2-D image is displayed.

More generally, a spatially organized virtual-processor machine such as CAM-8 can efficiently perform a variety of wavefront calculations: calculations that can be laid out in an n-dimensional space in such a way that we're only interested in the evolution of a wavefront through the space. This can be viewed as a way of performing calculations on CAM-8 that aren't uniform in space or in time. Functional simulation of synchronous logic provides a good example of such a wavefront calculation: a synchronous circuit is laid out in n-dimensions so that the direction of dataflow is always positive along one of the dimensions, and then we simulate each clock of the synchronous circuit by sweeping the signal wavefront through this dataflow-dimension once. Since the dataflow-dimension is virtual, it can be thought of as holding the time-dependance information for an $n-1$ dimensional spatial calculation, and so this is really just a generalization of static routing to arbitrary space-time logic. This technique has immediate application to the design of virtual-processor FPGA chips.

Finally, one of our new Physics Ph.D.'s this year was Mark Andrew Smith, who wrote his thesis on "Cellular Automata Methods in Mathematical Physics." This thesis includes a number of important new techniques for modeling physical systems with cellular automata, and also a very interesting technique for getting the most out of the efficient random-variable-generating capabilities inherent in the CAM-8 architecture.

1.3 Call for proposals

As mentioned in the introduction, we are planning to provide RA support to other groups here at MIT interested in collaborating with us on algorithm and software development for CAM-8. This would include physical scientists who want to develop CA algorithms of physical systems, and computer scientists who are interested in develop-

Figure 3: Real-time video-processing on CAM-8.

ing CA-based algorithms, languages, or systems software. The algorithms and collaborations discussed in the previous Sections give an idea of the range of areas already being explored on CAM-8. For a recent description of the project, applications, collaborations, software and plans, see [12].

2 Physics of Computation

Our current research into the Physics of Computation is the continuation of a long and productive train of research that our group has been involved in for over 15 years. This research produced many of the original results on the theory of reversible computation (including reversible cellular automata), and has more recently included pioneering work on lattice gas simulations of physics and results on Quantum Computation.

The thread that ties all of our research together (including our CA work) is an attempt to push the theoretical descriptions that people use to model computation, and those that are used to model physics, closer together: to make models of computation more physical, and to adapt computations to run on these more physical computers.

This has been a very forward looking endeavor: engineers are only now beginning to discuss reversible computing at conferences on low-power computers. Quantum-scale computing devices are only now being attempted in the laboratory. FPGA's are a descendant of CA's that have only recently become popular as computing components.

The recent result by Peter Shor, that a quantum mechanical computer can factor in polynomial time, has stimulated a lot of interest in the Theory of Computation community. The basic idea is that in quantum mechanics, a physical system can be thought of as performing many dynamical evolutions simultaneously, with only the result of one of them being observed at the end—quantum theory predicts the relative probabilities of seeing the various possible outcomes. If each of these dynamical evolutions is a distinct computation, then you have a uniquely quantum form of parallelism. Interference effects can make the probability of seeing the results of certain computations much more likely than others, so that effectively all of the probability can be put, in the case of Shor's algorithm, on states that contain the answer to the factoring problem.

We've been having discussions with researchers around the Lab and around MIT about this topic, aimed at understanding this result better and seeing if we can actually build a Shor-type quantum computer. We also recently had Peter Shor visit here and give a talk on his quantum factoring result, in a joint Physics of Computation and Theory of Computation seminar. Other recent seminar speakers also include:

Seth Lloyd A Technologically Feasible Quantum Computer.

Charles Bennett Quantum versus Classical Information: a Fruitful Dichotomy.

Ben Schumacher Qubits and Quantum Coding.

Tom Toffoli OCCAM, TURING, JAYNES, or How much can you get for how little? (An introduction to cellular automata).

Norm Margolus Cellular Automata Machines: Moving Towards Ultimate Computation .

Dan Rothman Simple Models of Complex Fluids.

Bruce Boghosian An Exact Theory For Lattice Gas Hydrodynamics

Claude Crepeau A Provably Unbreakable Quantum Cryptographic Protocol.

William Wootters Trying to Clone Quantum Information.

Paul Vitanyi Information Distance and Thermodynamics of Computation.

Peter Shor A Polynomial Time Algorithm for Factoring Integers on a Quantum Computer.

These talks have all been part of the Physics of Computation Seminar: a series on adapting computers and computations to the constraints of, and opportunities afforded by, microphysics; and on the development and application of the physical theory of computation and information.

Our Quantum Computation and our more theoretical CA researches are funded under ARPA's Ultra project (one of only two theoretical groups funded by this project). One of our physics Ph.D.'s this year was Michael Biafore, who got his degree working on research related to our Quantum Computing activities (thesis title: "Few Body Cellular Automata: a methodology for extracting useful computation from physical interactions"[5]). Mike is now a Post Doc in our group, and he was actually the instigator and driving force behind our application for the Ultra grant which now supports him.

Finally, the Turin (Italy) Workshop on "Quantum Computation" that we organized last year (along with Bennett, Penrose, and others) will be held again late this summer. Last year's meeting included all of the major workers in the fields of quantum cryptography and quantum computation, and we expect to have a similar group this year.

3 Conclusions

As a growing number of collaborators begin to use CAM-8, revolutionary new CA algorithms and physical models are being discovered. Meanwhile, as computer scientists contemplate exploiting physical dynamics at ever-decreasing size scales, we plan to continue to play an active role in the developing collision between Information and Mechanics.

References

[1] ADLER, C., D. D'HUMIÈRES, and D. ROTHMAN, "Surface tension and interface fluctuations in immiscible lattice gases," *Journal de Physique I* (France), **4**, 29–46, January, 1994.

[2] AHARONOV, E., and D. ROTHMAN, "Non-Newtonian flow (through porous media): a Lattice Boltzmann method," *Geophysical Research Letters*, **20**, 679–682, April, 1993.

[3] BIAFORE, Michael, "Cellular automata for nanometer-scale computation," *Physica D* **70** (1994), 415–434.

[4] BIAFORE, Michael, "Universal computation in few-body automata," *Complex Systems* **7** (1993), 221–239.

[5] BIAFORE, Michael, "Few-body cellular automata: a methodology for extracting useful computation from physical interactions," MIT/LCS/TR-597 (Ph.D. Thesis, December 1993).

[6] BOGHOSIAN, B. M., and W. TAYLOR, "Correlations and Renormalization in Lattice Gases," (submitted to *Phys. Rev. E*).

[7] BOGHOSIAN, B. M., and and W. TAYLOR, "Renormalization of Lattice Gas Transport Coefficients," in *Pattern Formation and Lattice-Gas Automata*, A. LAWNICZAK and R. Kapral, (eds.), American Mathematical Society (1994).

[8] CLEMENTI, Andrea, Russell IMPAGLIAZZO, Pierluigi PIERINI, "On the average-case complexity of the reversibilty problem for finite cellular automata," submitted to *PhCo '94*, Dallas, Texas.

[9] CLEMENTI, Andrea, Patrizia MENTRASTI, Pierluigi PIERINI, "Some Results on Invertible Cellular Automata," submitted to *Complex Systems* and *PhCo '94*, Dallas, Texas.

[10] D'SOUZA, Raissa, David MILLER, Brad SAFFORD and Yaneer BAR-YAM, "Dynamical scaling in a multiple regrowth model for diamond films," submitted for publication.

[11] GILLIAM, Harris L., *BISHOP: A framework for economic simulation using cellular automata*, MIT Bachelor of Science Thesis in Computer Science and Engineering, Aug 24, 1993.

[12] MARGOLUS, Norman, "CAM-8: a computer architecture based on cellular automata," in *Pattern Formation and Lattice-Gas Automata*, A. LAWNICZAK and R. Kapral, (eds.), American Mathematical Society (1994).

[13] MARGOLUS, Norman, "Cellular Automata Machines: a new kind of computer," to appear in the proceedings of the *Second International Conference on Computational Physics* (Beijing, September 1993).

[14] MARGOLUS, Norman, "Virtual Processor Emulation of Large Cellular Logic Systems," submitted for publication.

[15] MARGOLUS, Norman, "Spacetime circuitry on CAM-8," submitted for publication.

[16] MARGOLUS, N., T. TOFFOLI, "STEP: a Space Time Event Processor," *Tech. Rep. MIT/LCS/TR-592*, MIT Lab. for Computer Science (1993).

[17] Pierini, Pierluigi, "Real-time image equalizer with CAM8," MIT Information Mechanics Group Memo (1994).

[18] Pierini, Pierluigi, "Simulating long-range forces with cellular automata," submitted to *Transactions of the Society for Computer Simulation*.

[19] Pierini, Pierluigi, "Space-time structures for cellular automata," to appear in the proceedings of *ACRI '94*, Rende (CS) Italy Sept 29–30, 1994.

[20] Rothman, D., "From ordered bubbles to random stripes: pattern formation in a hydrodynamic lattice gas," *Journal of Statistical Physics* **71** (1993), 641–652

[21] Rothman, D., J. Grotzinger, and P. Flemings, "Scaling in turbidite deposition," *Journal of Sedimentary Research* **A64** (1994), 59–67.

[22] Rothman, D. and L. P. Kadanoff, "Bubble, bubble, boil and trouble," *Computers in Physics* **8** (1994), 199–204.

[23] Rothman, D. and S. Zaleski, "Lattice-gas models of phase separation: interfaces, phase transitions, and multiphase flow," *Reviews of Modern Physics* (in press).

[24] Smith, Mark Andrew, *Cellular Automata Methods in Mathematical Physics*, Ph.D. Thesis, MIT Department of Physics (May 1994).

[25] Toffoli, Tommaso, "Neural Networks," *Ecyclopedia of Applied Physics*, American Institute of Physics (to appear).

[26] Toffoli, Tommaso, "Cellular Automata," in *The Handbook of Brain Theory and Neural Networks*, MIT Press, 1994.

[27] Toffoli, Tommaso, "Occam, Turing, von Neumann, Jaynes: How much can you get for how little? (A conceptual introduction to cellular automata)," to appear in the proceedings of *ACRI '94*, Rende (CS) Italy Sept 29–30, 1994.

[28] Toffoli, Tommaso, "Quantum information, communication, and computation" MIT Information Mechanics Group Memo (1994).

[29] Toffoli, T., "3-D rotations by composition of special shears," MIT Information Mechanics Group Memo (1993).

[30] Yepez, Jeffrey, "A reversible lattice-gas with long-range interactions coupled to a heat bath," in *Pattern Formation and Lattice-Gas Automata*, A. Lawniczak and R. Kapral, (eds.), American Mathematical Society (1994).

[31] Yepez, Jeffrey, "Lattice-gas theory and computation," to appear in the proceedings of the AFOSR Mathematical and Physical Computation Conference, (Kirtland AFB, New Mexico, June 5 1994).

[32] Yepez, Jeff, Guy Seeley, and Norman Margolus, "Lattice-gas automata fluids on parallel supercomputers," to appear in *Computers In Physics*.