SFI Bulletin

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WHAT CAN WE CLAIM FOR OUR SCIENTIFIC MODELS?

SFI Bulletin

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The Santa Fe Institute is a private, independent, multidisciplinary research and education center founded in 1984. Since its founding, SFI has devoted itself to creating a new kind of scientific research community, pursuing emerging synthesis in science. Operating as a visiting institution, SFI seeks to catalyze new collaborative, multidisciplinary research; to break down the barriers between the traditional disciplines; to spread its ideas and methodologies to other institutions; and to encourage the practical application of its results.

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COVER
Giorgio Vasarim (1511-73)
View of Florence. Fresco
Palazzo Vecchio, Florence, Italy.

High School Students and Teachers Tackle Complexity Concepts with Starlogo Software

Diane Banegas

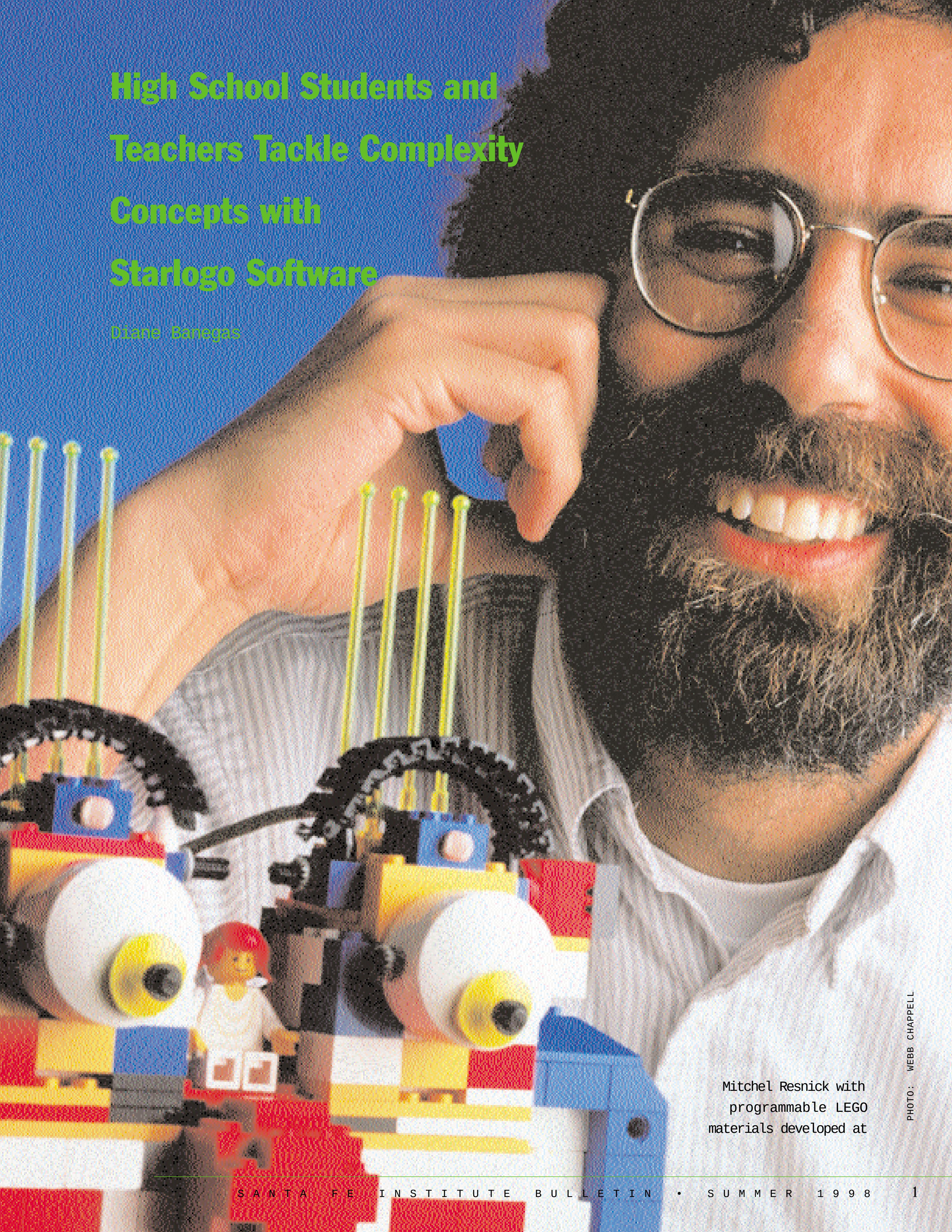


PHOTO: WEBB CHAPPELL

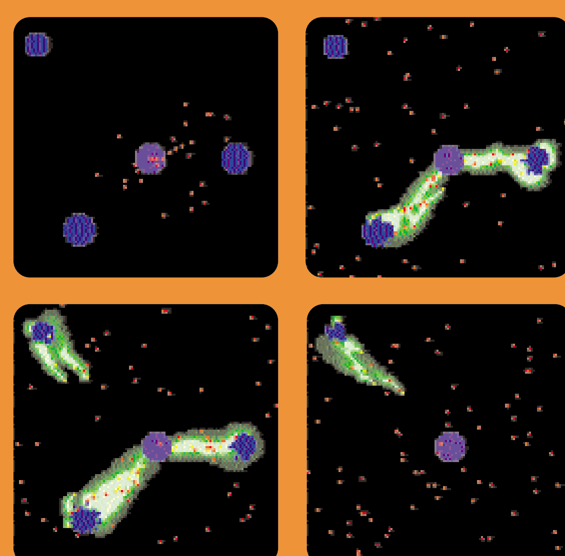
Mitchel Resnick with programmable LEGO materials developed at

What is the simplest way to teach high school students the concepts of complexity? The Santa Fe Institute believes one answer lies in a hands-on approach and a computer modeling tool known as Starlogo software.

This summer 10 teachers and 10 students from the area's public and private high schools will spend two weeks at the Santa Fe Institute using Starlogo software to develop simulations of decentralized systems such as traffic jams, ecosystems, and ant colonies.

Starlogo software, developed by Mitchel Resnick of the Massachusetts Institute of Technology (MIT) Media Lab in support of his research on decentralized thinking, is an excellent teaching tool because users can model their ideas without first having to learn a complicated programming language. Starlogo also has a proven track record for encouraging students to break out of conventional modes of thinking about complex phenomena.

"In some ways, the concept of a complex, decentralized system is counter-intuitive," said Larry Latour, the Starlogo workshop leader and associate professor of computer science at the University of Maine. Latour is a seasoned veteran of Maine's Upward Bound Math/Science Program for high schoolers. "Our culture leads toward a hierarchical structure and we tend to fall back on that as a way to describe systems." The truth is, Latour says, many systems—such as human settlements or flocks of birds—have no central controlling force. They have a large number of agents all interacting and adapting to each other and their local environments. Ultimately, a highly complex order emerges from the local interactions of all the parts. When students begin modeling these systems, their standard rules of reasoning break down, and they begin to develop the decentralized mindset necessary to understand how complex systems work.



A colony of Staglogo ants forages for food, creating trails with a pheromone. Each ant fol-

Each teacher is inviting one student to the camp. The pairs will act as learning teams with both teachers and students studying the same concepts and carrying out the same assignments. Chris Jakobs, a science teacher at the Desert Academy Middle and High School, likes the approach of teachers going to camp with students. "It's an honest situation," she notes. "The students will see that we, as teachers, are still learning." She adds that she's eager to spend two weeks immersed in the subject of complex, adaptive systems. "I want to see how it changes my thinking, and I'm excited by what the experience might bring to my teaching."

Participation in life-sized simulations can help students develop deeper understandings of dynamic systems. Participants then draw on their "first-

Vanessa Stevens-Colella, a camp organizer and graduate student in the Epistemology and Learning Group at the MIT Media Lab, says Starlogo was designed with high school students in mind. "Participatory simulations help students and teachers develop new understandings of complex systems," she says. "As an educational tool, Starlogo encourages students not only to observe, but also to experiment, manipulate, and learn."

Described simply, Starlogo software presents a large number of active agents, called "turtles," with the ability to move in any direction over a patchwork grid that represents the local environment. Each camp participant will use these same software components to simulate an example of a complex adaptive system, be it the foraging behavior of ants or the antigen-antibody interaction of the human immune system.

Simulating the system is only the beginning. As part of the exploration process, the participants will be required to analyze, validate, and modify their simulations. One goal for the participants will be to develop group instruction methods in which individuals "act out" the mechanisms of complex adaptive systems and through their actions experience first-hand the emergent phenomena inherent in their explorations.

All workshop participants are expected to produce a poster, computer model or models, written description, and web site for their exploration. The teachers are also expected to come away from the workshop with specific examples and applications for using modeling and simulation as a component of their overall teaching strategy.

All of the teachers participating in the workshop helped plan the structure and curriculum. "An important part of this project is to encourage linkages within the Santa Fe community of secondary science teachers, not only between the teachers and SFI, but among the teachers themselves," says Ginger Richardson, SFI coordinator for the summer event. "As far as we're concerned this is a five-way equal partnership involving Santa Fe students and teachers, the Institute, the Media Lab, and the University of Maine. We each bring a different kind of expertise to the table, and I think it will be a provocative mix."

Partial funding for the camp comes from the National Science Foundation. Local support is provided by the McCune Charitable Trust and The Rose-Legett Foundation.

The format for the nine-day program will include one-on-one mentoring and guest talks by SFI researchers. To address the interests and needs of both students and teachers, the students will attend each day from 9 a.m. to 3 p.m., while the teachers stay on for two additional hours to address specific issues on teaching and curricula.

The "faculty" staffing this workshop is multi-generational and multi-institutional. In addition to Latour and Stevens-Colella, SFI researchers will provide daily "stimulation" talks. Other staff will include a National Science Foundation postdoctoral fellow, University of Maine and SFI graduate students and undergraduate interns. Finally, the secondary students and teachers themselves will function as co-teachers and learners.

James Taylor, a science teacher at Santa Fe Preparatory School, says he's looking forward to watching how the students learn these concepts because it will be important for introducing and teaching the subject later. He sees the value of the Santa Fe Institute as a local resource for teachers and students, especially with its globally relevant research on complex adaptive systems. "Our society is so complex, yet we're wired culturally to think only of centralized systems," he says." It can lead us to do powerful things without thinking of the web of consequences of a single action by a single individual."

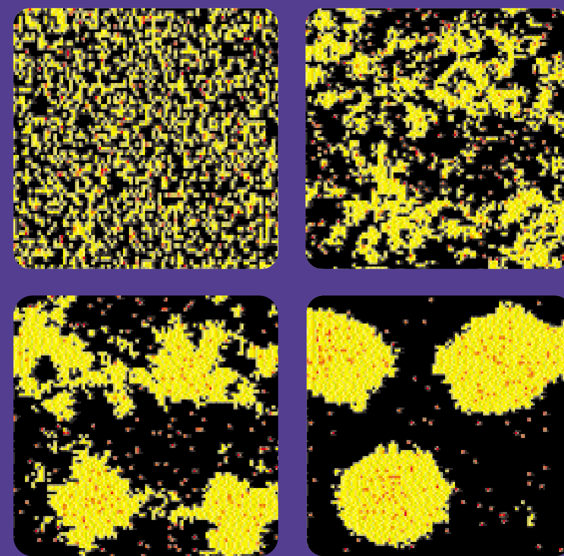
For Diane Catron, a former science faculty member at Santa Fe High School and current member of Santa Fe Prep's faculty, the workshop is an opportunity to learn how to integrate a new subject and new teaching method into her classroom. "I'm not an expert with computers, but I'm interested in observing this teaching approach," she says. "As a biologist, I believe centralized systems are the exception rather than the rule." Getting her students to think about familiar subjects in new ways isn't always easy, she admits. "I'm guardedly optimistic that the Starlogo workshop will prompt kids to look beyond simple cause-and-effect relationships and consider things in a new and more complex way."

The Institute's plans for the Starlogo workshop are long-term. If this year's pilot program is successful, it may become an annual event. The organizers intend to incorporate feedback from attending students and teachers. As the program matures, the Institute plans to consider sponsoring a packaged program including general software and course material for distribution beyond Santa Fe. One possible channel of distribution would be a World Wide Web site with materials for downloading.

Since its inception in 1984, the Santa Fe Institute has reached out to schools in the Santa Fe area with workshops, a lecture series, mentoring for New Mexico's annual "Adventures in Supercomputing" competition, and an awards program for outstanding high school seniors. The Starlogo workshop marries the Institute's multidisciplinary approach to the study of complex adaptive systems, and its tradition of operating as a visiting institution to introduce new ideas and methodologies to other institutions. Scientists from all over the world have visited or conducted research at SFI; Latour believes the Institute's work is just as relevant to high school science teachers.

"The problem has always been that high school teachers have a heavy work load, and they don't have a great deal of time during the school year to take on something like this," Latour says. "The workshop provides an educational curriculum centered around an easy-to-use simulation tool that enables students and researchers of all ages to think synthetically and analytically about complex adaptive systems."

Diane Banegas is a writer who lives in Santa Fe.



Starlogo termites gather wood chips into piles without any centralized "leadership," a good example of organized, global patterns arising

By wearing small, communicating computers, called Thinking Tags, individuals can become actors in computationally-supported simula-

Mind-Sets

THE WAY WE LOOK AT THE WORLD

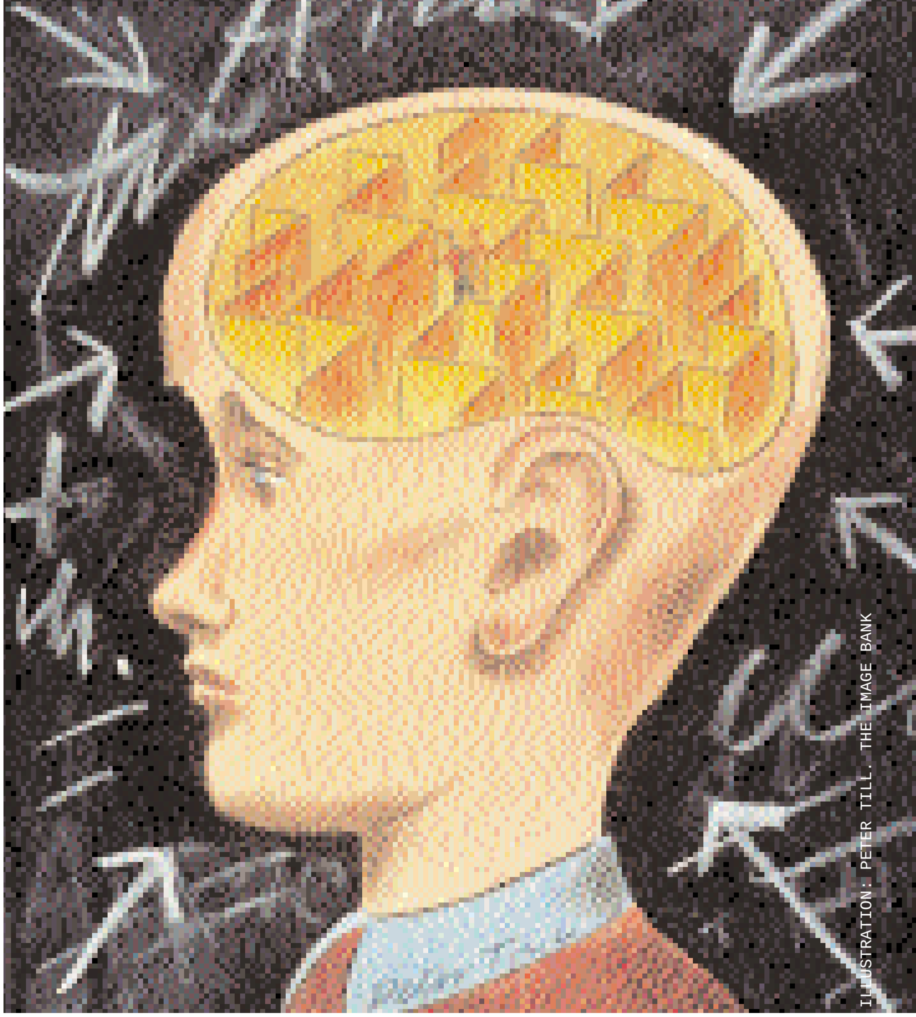


ILLUSTRATION: PETER TILL, THE IMAGE BANK

In May, a group of SFI trustees unknowingly circulated a virus that became an epidemic. It reached no farther than the walls of the room in which they attended a mock-cocktail party, but its ramifications were much farther-reaching.

The trustees attending the May SFI Science Symposium were sampling the kind of activity high school students and teachers will experience at the Starlogo workshop this summer.

During the symposium, the Media Lab's Mitchel Resnick and Vanessa Stevens-Colella previewed new technology being developed at MIT. This particular technology enables people to become active participants in life-sized, computational simulations of dynamic systems. Using Thinking Tags—small, name-tag sized computers that communicate with each other by infrared signals—a thin "layer" of computation is added to participants' social interactions, transforming a group of individuals into a dynamic simulation.

Each person within the SFI group of about 35 was given a tag to wear. As people interacted, their tags also interacted. The combination of the people and the tags formed a "digital ecology" in which both humans and computers participated. While the tags kept track of the computational system model, individuals were free to interact with one another and participate as the system unfolded.

In this particular case, unbeknownst to the participants, people became active agents in the simulation of an epidemic, with an electronic "virus" jumping from tag to tag. Following the simulation, the group worked on a collective analysis of the disease dynamics. Was the transmission of the disease probabilistic? Did the disease have a latency period? Are some people more susceptible than others?

Workshop organizers believe that active simulations like this one, along with software like Starlogo, will help students experiment with complex systems and develop better intuitions about the mechanisms that govern dynamic interactions.

In March, ten distinguished scientists joined the Santa Fe Institute research community as Science Board and External Faculty members. Although their home institutions are elsewhere, these scholars play important roles in the Institute's scientific leadership and research programs.

SCIENCE BOARD

William Greenough is professor of psychology, psychiatry, and cell and structural biology at the University of Illinois at Urbana-Champaign. As his title indicates, Greenough's intellectual interests are wide-ranging. His research on the brain is grounded in the laboratory, where his experiments have contributed significantly to understanding of synapse development. He has recently discovered the way a protein—known as mental retardation factor x—plays a role in synapse development. (When it is absent development proceeds badly, hence the name.) Greenough has a long-standing commitment to communicating research results at the frontier to a broad community including both neuroscientists and behavioral scientists—as evidenced by the six book chapters he has written in the past three years.

Perci Diaconis, professor of mathematics and statistics at Stanford, is a statistician with a breadth of scientific interests. Topics to which he has made substantive contributions include computational complexity, multivariate analysis. Bayesian estimation theory, random matrices, random number generators, random walks, Monte Carlo theory, number theory and interacting particle systems. This long list does not include his work in the area of "cognitive illusions"; Diaconis is a professional-level magician as well as a leading debunker of paranormal psychology.

Stephanie Forrest, associate professor in computer science at the University of New Mexico, is a long-time member of the SFI community. Currently an External Faculty and Science Steering Committee member and a former two-term member of the Science Board, Forrest's range of interests as a computer scientist resonate strongly with the Institute's scientific goals. Her early research was on the implementation and analysis of classifier systems as proposed by John Holland. Since then, she has been a leading researcher in investigating the theoretical concepts of "emergent computation" (her term, one now widely used). She has also been a leader in exploring the applications of a broad range of biological mechanisms, such as the pattern-recognition features of the human immune system. This exploration has led to the development of novel computational constructs such as computer security systems which use pattern-recognition features to find viruses.

Donald Glaser is professor of physics and of molecular and cellular biology (Division of Neurobiology) at the University of California at Berkeley. Glaser was awarded the Nobel Prize in 1959 for the invention of the bubble chamber, one of the principle instruments that drove particle physics. After a long career as a particle experimentalist, he moved on to research in cellular and molecular biology, part of which involved the design and construction of a machine for the automated recognition of patterns in cell shapes and cell colonies. This led to his co-founding one of the first genetics engineering firms, Cetus. Most recently Glaser has been working on the psychophysics of vision, concerned with theoretical modeling of the neural mechanisms supporting human perception and with the experimental investigation of how humans detect motion, depth, and texture.

Among the experimental biologists who have become newly active in SFI research over the past year is **Leland Hartwell**, professor at the University of Washington and president of the Fred Hutchinson Cancer Research Center. Our current understanding of the cell cycle, the process through which new cells are formed by the division of existing ones, depends essentially on his contributions in this area. In particular, Hartwell has exploited the potential of yeast genetics and molecular biology to explain steps in the control of cell division that apply to all higher organisms. This work is not only of fundamental importance for understanding the process of cell division, but it also illuminates the pathophysiological mechanisms responsible for the malignant transformation of cells.

TEN ELECTED TO INSTITUTE SCIENCE POSTS

Arthur Jaffe is a mathematician and physicist whose scientifically formative years were spent at Princeton, Cambridge University, and Stanford. He joined Harvard about thirty years ago, where he serves as Landon T. Clay Professor of Mathematics and Theoretical Science. Jaffe was a founder of "constructive quantum field theory," developing new analysis and probability theory to make possible a full non-perturbative study of quantum field theory and renormalization theory. Incorporating ideas from supersymmetry and string theory, Jaffe developed a theory of geometric invariants for quantum spaces. Jaffe won the Dannie Heineman Prize of the American Institute of Physics, and the Mathematics and Physics Prize from the New York Academy of Science. He served as trustee of the Mathematical Sciences Research Institute at Berkeley, and for two terms as President of the International Association of Mathematical Physics. Currently he is president of the American Mathematical Society—where he has taken a national role on questions of science funding.

David Raup's research has continually broken new ground, changing the way paleontologists and biologists think about evolution and the history of life. Professor emeritus at the University of Chicago and a research associate at the Field Museum of Natural History, Raup is regarded by many as the founder of analytical paleontology. Recently Raup, together with Jack Sepkoski, shook the paleontological community with their discovery of a 26-million-year periodicity in the occurrence of mass extinctions. This analysis led to a search by astronomers for one of the possible causes of the periodicity, a companion star in orbit around our sun. No companion star has been found, but Raup's analysis has survived all challenges and the periodicity remains a robust pattern and an outstanding unsolved problem.

Mary Jane West-Eberhard is an internationally recognized leader in the study of social insect behavior. A staff scientist at the Smithsonian Tropical Research Institute, West-Eberhard's contributions to the understanding of kin selection, sexual selection, and social competition are regarded as seminal, and her research on tropical wasps defined to a large extent "wasp behavior" as a field of study. Her current research interests focus on phenotypic plasticity and evolutionary developmental biology, work that should have an important impact on the field of social insect behavior, and also on more general aspects of evolutionary thinking in biology. West-Eberhard is in the final stages of writing a book on phenotypic plasticity, development, and evolution that proposes a theory of biological organization to unify work in genetics with studies of the always environmentally-sensitive phenotype.

EXTERNAL FACULTY

Avidan Neumann has had a long association with the Institute. From 1992-1994 he was a SFI postdoctoral fellow working with Alan Perelson on immune system modeling. Prior to that he worked as a postdoc for one year with Lee Segel and for a number of years on his doctorate with SFI science board member Gérard Weisbuch. Subsequent to his years at SFI, Neumann worked at Los Alamos National Laboratory with SFI faculty member Bette Korber and with Perelson on AIDS-related projects. Currently an assistant professor in life science at Bar-Ilan University in Israel, Neumann continues to collaborate with Perelson researching hepatitis C virus as well as HIV.

Ricard Solé is head of the Complex Systems Research Group at Polytechnic University in Barcelona. He has been working for some time on spatio-temporal dynamics in ecology, evolutionary dynamics, self-organized critical phenomena, social insects and computation, rain forest diversity models and random networks. More recently he has taken up research on the dynamics of RNA viruses, stochastic resonance, the quantitative characterization of complexity, and the connection between morphogenesis and evolution.

Scientific Models: Claiming and Validating

Cosma Rohilla Shalizi

> **It is easier to make a theory of everything than it is to make a theory of something.**
>
> —Aharon Katchalsky, as quoted by George Oster

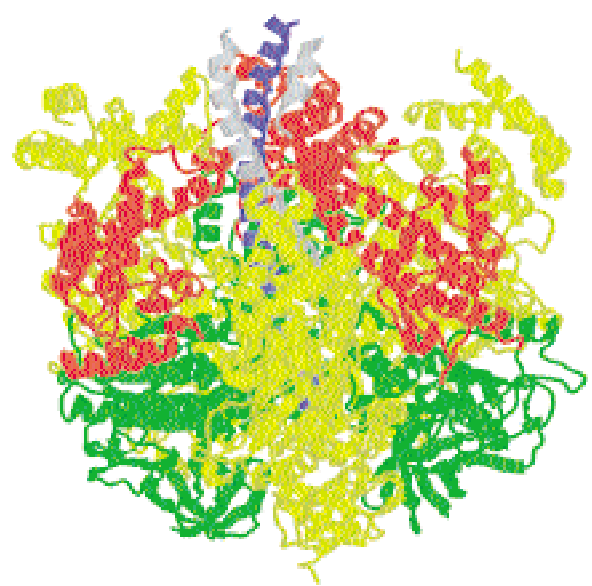
This spring's SFI Science Board Symposium took as its theme "Scientific Models: Claiming and Validating." The goal was to address the question—in the context of specific social, biological, and physical systems—of what can be "claimed" for a model that has been constructed to describe that system.

The symposium consisted of three talks and general discussions, and while they weren't chosen to exemplify Katchalsky's aphorism quoted above, they might as well have been.

THE WORLD'S SMALLEST ROTARY MOTOR

SFI Science Board member George Oster, a professor of biology at UC Berkeley, led off the program with a talk on "The World's Smallest Rotary Motor." The general issue addressed by Oster's work is how cells turn chemical energy into mechanical force, and, in particular, how the protein ATP synthase pulls off the trick.

To begin with, what does ATP synthase do? Principally, it synthesizes ATP (adenosine triphosphate) from ADP (adenosine diphosphate) and phosphate. ATP is then used as the energy source for almost all cellular reactions. (This is why ATP synthase is sometimes billed as "the most important protein in the universe," a description Oster modestly admits "may not be entirely hype.") In short, it is an important and ancient protein, so "if any molecule has been optimized by evolution, this is it."

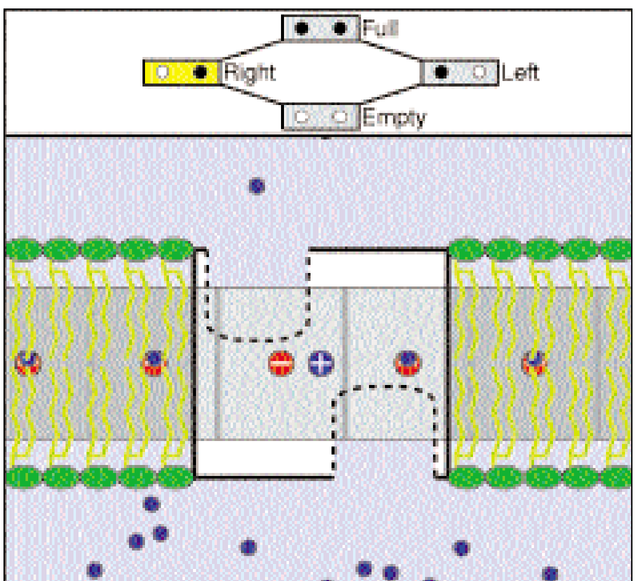


A perspective view of the alpha3 beta3 gamma.

The ATP synthase has two components, F0 and F1. The first, F0, deals with proton gradients; the second, F1, with the synthesis of ATP. Each can act as a "rotary motor," the pair of them being connected by a shaft, giving the whole affair the look of a lollipop on an ornamental stand. Physicists like Oster are conditioned to associate the notion of "engine" with "heat" since they are drilled from the start to tackle motors as problems in thermodynamics. When one measures the efficiency of the synthase, however, it turns out to be over 90 percent, with no temperature gradients worth mentioning. ATP synthase certainly cannot be a heat engine, and so physicists need to consider it in a new way.

What is of great interest is the way the structural biologists have gone over ATP synthase atom by atom in its different conformations. Very detailed simulations of molecular dynamics show that, while there's a lot of jitter, the important conformational changes of proteins can be decomposed into shearing motions and hinged bending motions. Using this information, and the known detailed structure of ATP synthase, Oster was able to write down a very simple model—a "tinker-toy model"—for the mechanical and elastic properties of the synthase, incorporating only those hinges and shears. The tinker-toy is only for illustration; the real model is a set of mechanical equations, fairly straight-forwardly deduced from Newton's laws, in which drag is opposed by stochastic, ultimately chemical driving forces.

The solutions of these equations are in agreement with experiment, qualitatively and quantitatively. Moreover, when run in reverse—when provided with outside torque, and used to either synthesize ATP or build up a proton gradient—the equations again are in quantitative agreement with experiment. This is, as Bob May said in the discussion afterwards, "mathematical biology at its best."



A side view of the F0 motor. By Timothy Elston, Hongyun Wang and George Oster,

Two related evolutionary issues occupied that discussion, with lively input from Murray Gell-Mann, Stuart Kauffman, Philip W. Anderson, George Lakoff, and Harold Morowitz, among others. The first was the optimality of ATP synthase. There is extraordinarily little variance in the protein across species—you can take parts from *E. coli*, and parts from cows, and put them together to get a working protein. This, together with its very high mechanical efficiency, suggests that ATP synthase is about as good as proteins working on its general lines can get; but we can't rule out the possibility of a radically different design which works as well as the actual one.

The second issue was whether those specific ways of functioning are the only way of doing ATP synthase's job. Partly this depends on how many different ways there are to do exactly the same job as ATP synthase (nobody knows; but Oster said there are known to be workable alternatives to the designs of some other molecular motors) and how many ways there are to change that job by tweaking other aspects of biochemistry, e.g. by using something other than ATP.

PUNCTUATED EQUILIBRIA IN PHYSICS, BIOLOGY AND ECONOMICS

"Punctuated equilibrium" is a phrase coined by paleontologists Steven Jay Gould and Niles Eldredge to describe a pattern they saw in the fossil record—a pattern of species remaining pretty much unchanged for long periods of time, and then going through a (geologically) brief spurt of change.

Per Bak, of the Niels Bohr Institute in Copenhagen, believes he can see this pattern in many places other than the fossil record, and even give it a mathematical characterization. The signatures of punctuated equilibrium, he says, are, first, a power-law distribution of event sizes (suitably defined) where there is no characteristic size for events, but the number of events over a certain size is inversely proportional to some power of that size.

The second sign he calls "1/f noise," where, again, events are distributed over all time-scales, but the power or size of events is inversely proportional to some power of their frequency; really big changes are rare, but not exponentially so. Finally, he claimed that punctuated equilibrium involves the assertion that "catastrophic" events are internally generated, as opposed to being the effects of external causes, like large rocks falling from the sky.

Power laws are well-established for some phenomena like the strengths of earthquakes and extinction rates, and, more controversially, for prices of stocks and other securities. (If it is true that changes in securities prices follow a power law, and the power law shows that the changes are internally generated, this undercuts one of the important traditional justifications for securities markets, namely that they effectively pool and evaluate all the available external information about the true worth of commodities and companies.) Acting on the assumption that punctuated equilibria are common, it is natural—at least for a physicist—to ask about a "general mechanism" which will produce them, one for which "the details don't matter."

Bak suggests that this general mechanism is to be found in statistical physics's notion of the critical point, at the boundary between two radically different states (for instance, between liquid water and steam, where the critical point is 100 degrees centigrade at sea level, and noticeably lower in Santa Fe). At critical points, the response to perturbations can (Bak says) be extremely nonlinear, and the power-law distributions and 1/f noise depend on this. In fact, power-laws are generically found in physical systems close to the critical point. What Bak has proposed are models which are not just critical, but "self-organized critical."

Instead of needing to have parameters (like temperature and pressure) tuned to get them to the critical point, their own dynamics will take them there, keeping them in stable but critical condition. "You cannot make a realistic model of California to explain earthquakes" —so simple models will have to do. One of the very simplest models which exhibits self-organized criticality is the so-called "sandpile" model, where we imagine ourselves to be dribbling sand from above onto a small pile. Friction between the grains can balance gravity only up to a certain slope, so we imagine that, when enough sand has built up at one location to exceed that slope, it shifts to some down-hill locations. If these are already near the critical slope, sand will flow from them as well, and so on, generating an avalanche. All of this can be formalized with two or three rules and just integer values for the height. This displays all the power laws (avalanche size, time between avalanches at a site, etc.) one could want, the 1/f power spectrum, and so forth.

Now, what makes us think that this toy model can teach us anything about the real-world systems with similar statistical features? Bak answers: "Our intuition from physics." There, powerful mathematical methods have established that many properties (including the power-laws) are the same for all critical systems in the same "universality class," regardless of their detailed physical construction. This being so, we use the simplest model in the right universality class, since trickier, more realistic models give no more "insight into the type of beast we are dealing with."

So, what does Bak say falls within the universality class of this "theorist's sand"? Well, actual granular materials (at least sometimes—depending on physical details, like the ratio of the length of the grains to their width); earthquakes, as described by a simple mechanical model with "stick-slip" motion; evolution, where avalanches get mapped onto extinctions, and the different sites of the sandpile model to different species; and the actions of many separate traders on the stock-market, where each trader is mapped onto a different site, and avalanches are waves of buying or selling a certain stock.

SCALLA/ART RESOURCE, NY

The discussion following Bak's presentation was wide-ranging and heated, with Bob May taking the lead in arguing against Bak. The two most important issues were those of external events and model construction. There is a strong consensus among biologists that at least the five great mass extinctions were caused by exogenous events—most notoriously, that at the end of the Cretaceous by a meteorite impact. A second point which was urged was that there are really very many ways, many statistical mechanisms, which generate power-law distributions, which would undermine the arguments about universality classes.

Florentine School
Procession of a guild with the Pala di San Giovanni in Florence.
Cassone painting. Distemper on wood. 15th c.

BANKING MARKETS IN RENAISSANCE FLORENCE

As University of Chicago political scientist John Padgett said, "Banking Markets in Renaissance Florence" is the "Florentine history" title for his presentation; the Santa Fe Institute title would be "The Co-evolution of States and Markets." Padgett's heart is with the Florentine title. That is, he doesn't look at Florence as a particular instance or test case of a general model of how states and markets co-evolve. Rather he wants to understand that co-evolution "primarily to understand Florence." The research began with the goal of understanding political parties in Florence, and he was "driven by the state itself" to look at the influence of markets on the politics, and of changes in the state on markets, especially in banking.

There is a long and very well-established body of work on the relation between markets and state structures, namely political economy, which Padgett accepts. However, being largely about the effects of state policies on markets, it's inapplicable to the present case. Not only was the Florentine state made up of exactly the same people as its business firms, serving their few months in the government of the republic, meaning that there was no distance, really, between those who made policy and those affected by it, but political economy is silent on the "constitution of social agents," the way agents (like firms or political divisions) get built up, which is precisely what Padgett wants to know about.

When one examines the data from the records of the Florentine guilds, principally that of the bankers, says Padgett, one can see four distinct kinds of firms—all of them partnerships—succeeding each other in turn, and rather abruptly at that. At the beginning of the 14th century partnerships were made within large, patrilineal families, grew to great sizes, and competed with each other viciously (e.g., conspiring on the city council to have business rivals exiled and their property expropriated). These were followed by much smaller partnerships arranged on guild and neighborhood lines, between masters and apprentices, pooling together resources for large projects and all in all more "solidaristic"; then "multi-divisional firms" where one businessman would join one partnership in (say) wool, another partnership in silk, a third in banking proper, and so on; and, finally, rentier firms, with a separation between owners and managers. In each case the different organizational form was "socially embedded," each "mobilized" a different sort of social raw material—first families, then guilds and neighborhoods, then social classes and marriage alliances within them, finally patron-client networks and political factions.

What Padgett set out to explain is why, since Florence at all these times had families, guilds, social classes and factions, now one and then another of these provided the raw material for building economic agents. The answer, "driven very much by what I see in my data," is state formation. The lines along which firms were formed were also the lines of division of Florentine politics. The advantage of forming partnerships with political allies is that, first, you can have more trust in your partner, and spend more time thinking about how to make money, rather than about whether he's going to have you exiled or poisoned, and, second, there are institutionalized recruitment channels—you can form a partnership with your nephew or the person on the next street over or your brother-in-law, with little effort at searching out a suitable candidate. Is this so? That is, do the changes in organizational form track the changes in politics? It seems that they do.

At the beginning of the period, Florentine politics was dominated by the rivalry of the great families, and the shift from family to guild firms took place at the same time as these elites seized control of the guilds. The shift to "multi-divisional firms" coincided, not just with Florence becoming the mediator for the whole European economy, but with "classic Marxian class warfare" as well. The elites were exiled and expropriated, a worker's republic was set up, and when the elites returned there were massacres in the streets, and, not surprisingly, the inter-class partnerships of the guild period were gone. So it looks rather like changes in market structure grew out of changes in organizational form, which grew from changes in politics, and especially in changes in how the state was constituted.

These changes in the state were, some of them, triggered by external crises, but in what Padgett says is a "predictable" way. When the crises arrive, and previously existing divisions (say, between families) are exacerbated, then political actors mobilize some other network as an instrument in their struggle, as an extra source of power. In time, these other networks move from being tools to being identities, the things on which political divisions are based, and the wheel is ready to turn again.

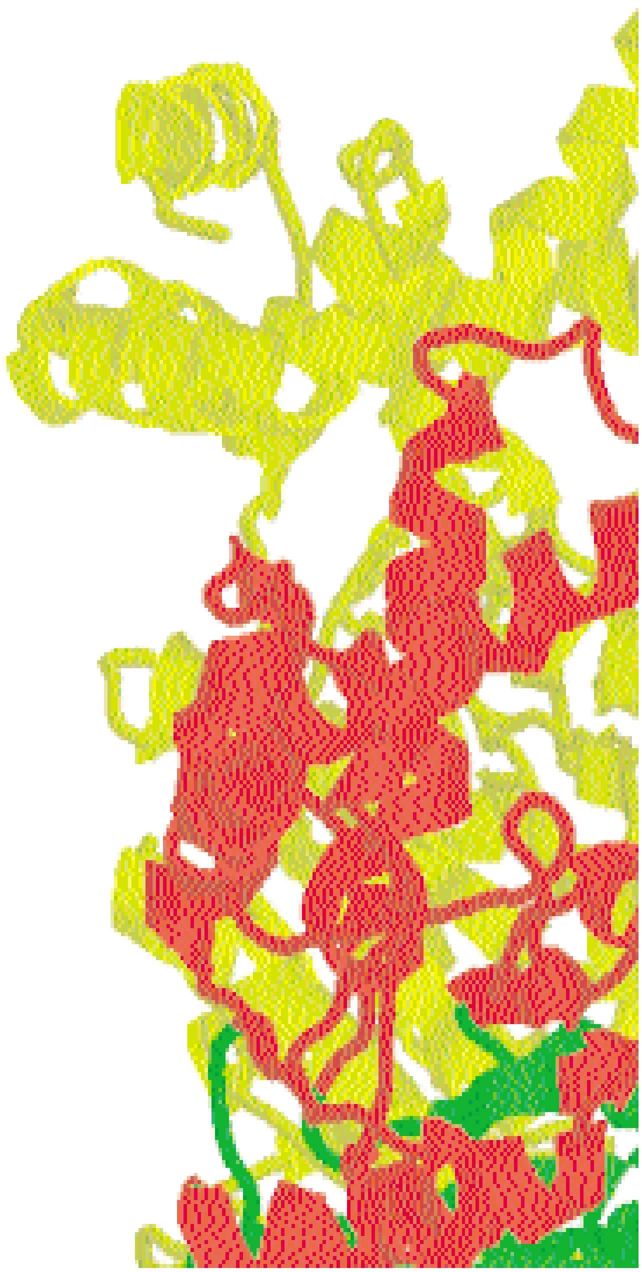
REFLECTIONS

If the goal of this symposium was to show the diversity of the things which get lumped together as "models," it succeeded, almost to excess. Both Oster and Bak are, for instance, physical scientists trying to answer questions of biology, but in completely different ways. In Bak's work, the "details don't matter," as he says, just the elucidation of a single, unifying general mechanism. Oster, on the other hand, immerses himself in biological detail—not just the structural studies which say where every single atom is, but knowledge of the function of a single enzyme, and exceedingly detailed genetic work which enabled him to identify key amino acids in a particular sub-unit. Padgett's work is something else again, even more detail-dependent but without the formal, mathematical structure of the physicists.

Some of the speakers professed to be mere slaves of their data, others confessed to prolonged trial and error. Nobody said anything very original about how models get built, or how they should be, and it was probably unreasonable to expect otherwise—good musicians are rarely good musicologists. Validation for models like Oster's is, in principle, straightforward: if it fits the known structure and kinetics of the enzyme, and agrees quantitatively with experiment, then the model does all it can be asked to do. Things are trickier for Padgett, since most of the data which the model is supposed to fit were used in putting it together, making agreement between the two less than compelling evidence in the model's favor. But this is a common problem for historical hypotheses, and the solution is new data, e.g., for guilds other than banking, or even cities other than Florence; within this description of one state and one set of markets there is a theory of states and markets in general hinting politely to be let out. (The model would probably need to have some formal backbone put into it first, though, rather than leaving it in its present verbal form.)

It is not at all clear what validation would even begin to look like for as all-encompassing and ambitious a notion as Bak's self-organized criticality. If it were the only way to get certain statistical properties, and earthquakes, evolution, etc., showed those properties, then that would be strong evidence that a SOC-like mechanism was at work; but it seems that there are other ways of generating such distributions, which do not involve self-organized criticality (for instance, the Newman-Sneppen model of extinction, where all extinctions are caused by exogenous stresses). The only way of figuring out which mechanism is active in particular cases would seem to lie in studying the details of that particular system, squashing the hope of finding general, details-independent mechanisms.

Cosma Shalizi, University of Wisconsin, is currently a graduate fellow at SFI



UNDERGRADUATE INTERNS HEAD WEST TO SANTA FE

PHOTO: JULIE GRABER

Every summer the Institute welcomes a small number of highly motivated and extremely talented undergraduates who benefit from exposure to the rich interdisciplinary mix of ideas at SFI. Students are matched with one or more mentors with whom they work on meaningful research problems. Through the process, the interns can make significant contributions. These mentorships have produced continuing collaborations and have resulted in several co-authored papers in the refereed literature. This summer SFI welcomes six participants to this NSF-supported program.

Silas Alben is photo editor for the Harvard Crimson. When not in the darkroom at Harvard, he concentrates on his junior-level physics/math major. His research interests cover all areas of mathematical applications including physics and also subfields of economics, biology, and computer science. Last summer at the Weizmann Institute of Science, Alben worked at implementing simple neural nets to help find a better amino acid contact potential for proteins. He has worked as a research assistant at the Harvard University High Energy Physics Lab and was a National Science Foundation fellow with the University of Michigan High Energy Spin Physics Group.

Hozefa Botee is working towards a double major in chemistry and computer science at the University of Florida, where he just completed his junior year. Botee's main research interests are in physical biochemistry/structural biology and theoretical quantum chemistry. His aim for his SFI experience this summer is to gain greater familiarity with physical biochemistry and to learn about how computational methods involving complex systems can be applied to problems in molecular biology.

Michael Campos' major at Northwestern University is the Integrated Science Program, an interdisciplinary effort that presents the major sciences in a sequence that encourages their conceptual integration while breaking down the barriers between the course topics. During his internship at SFI he intends to focus on modeling biological processes and studying their emergent properties. Campos' summer job last year was in London at the pub Swift and Stump, where he "evaluated the clientele's thick accents and prepared their drinks."

Massachusetts Institute of Technology junior **Christopher Douglas** has been working with Neil Gershenfeld this past year on the theory of time-series embedding. His current focus within this project is on developing new stochastic cluster weighted modeling algorithms. While at the Institute, he hopes to explore extending existing network algorithms and cellular automata models to simple manifolds, or to develop a simple dynamic distributed inference model. A founding editor and writer of MIT's newest newspaper, *The Observer*, Douglas also has experience in creative and nonfiction writing. He spent part of last summer at the Squaw Valley Writers' Conference in California.

Justin Werfel is a junior physics major at Princeton University. He notes, however, "that being so narrowly focused on one area for the rest of my life would really bother me," so he's concurrently minoring in math, engineering physics, computer science and biophysics. Werfel will focus on an SFI project with a strong physics component but combined with biology in some way, perhaps through neural networks, cellular automata, or models of evolving systems. He is especially interested in distributed learning. Werfel is president of the Juggling Club at Princeton, and last autumn was the announcer for the 1997 football season.

Jason Wyman studies physics at Middlebury College where he just completed his junior year. Wyman has been a teaching assistant in physics for the past three years at Middlebury, and last summer he worked at a biotech firm in the Midwest developing and implementing a rapid prototyping process for medical modeling applications. At Middlebury, sports—especially hockey and skiing—compete with academics for Wyman's time.

Renaissance Resonates with "Algebra" of Novelty

REX GRAHAM

THIS SUMMER, EXTERNAL FACULTY MEMBER JOHN PADGETT HOSTS A WORKING GROUP ON STATE AND MARKET FORMATION AT SFI

PHOTO: JULIE GRABER

A FEW YEARS AGO IN SANTA FE, the ghosts of Donatello, Masaccio, and Brunelleschi came out to dance, but not at the city's open-air opera. It was 3 a.m., an appropriate hour for poltergeists of the Renaissance pioneers of sculpture, painting, and architecture. It occurred in a darkened adobe house on Gonzales Street where a chemist lay reading a scholarly paper under a lamp. He was plowing through a treatise by University of Chicago political scientist John Padgett on the upheavals in 15th century Florentine society when it dawned on him that the sudden flowering of the Renaissance resembled the abrupt physical transitions of many chemical reactions. He was mesmerized.

SCALLA/ART RESOURCE, NY

Ambrogio Lorenzetti.
Effects of the Good Government in the City. 1338-39.
Palazzo Pubblico, Siena, Italy

"I couldn't put it down," said the chemist, Walter Fontana. "There was a kind of natural resonance in Padgett's analysis of Florentine society leading up to the Renaissance with how the first self-maintaining, self-reproducing cell must arise, or how any new paradigm of organization comes into existence."

The next day, as planned earlier, an excited but fatigued Fontana described Padgett's research to a group of SFI scientists, including Padgett himself. SFI pioneered this kind of interdisciplinary cross-fertilization 14 years ago and now is famous for it. The Institute's inclusion of Padgett's work reflects its effort to explore complex adaptive systems like biological evolution or the behavior of securities markets from unusual vantage points.

Padgett's ongoing research and his discussions with Fontana and others emboldened him. For example, he argued in a paper published this year in the journal *Theory and Society* that Florence "can be considered the birthplace of mercantile capitalism." He argues that novel uses of money, art, science, and politics created a new social alchemy in Florence in much the same way that a tetrahedral carbon atom takes on different properties depending on the elements it covalently binds to, and the links those elements make with other atoms, and so on.

Domenico Lenzi. The grainmerchant.
Italy, 14th c.
Biblioteca Laurenziana, Florence, Italy

SCALLA/ART RESOURCE,NY

"Walter and I, independently of each other, happen to place a great deal of causal weight on the 'algebras' of interactions leading very frequently to unintended institutional and personal novelties," says Padgett. He officially credits Fontana and other Institute scientists in his scholarly papers on the rise of the elite Medici family in 15th century Florence.

Padgett's research conclusions are based on ingenious interpretation of voluminous data. He has spent months in Florence poring over archived records of marriages, dowries, and other public transactions. These led him to conclude that at the birth of the Renaissance, the Florentine families that dominated banking, wool manufacturing, and other areas of commerce maintained their status and power through an elaborate system of political patronage and strategic inter-marriages. Padgett's analysis of 38 prominent Florentine family trees and the marriages of 298 families of lesser renown revealed an abrupt shift at the start of the Renaissance. He maintains that the shift, combined with other factors, eroded the political influence of elite Florentine families. At the same time, the previously excluded middle class united behind one family—the Medici. Coincidentally, vital accoutrements of modern business—double-entry bookkeeping, marine insurance, partnerships with branches, holding companies, bills-of-exchange, and international banking—were invented in northern Italy about the same time and quickly spread.

Completing the "phase transition," a term borrowed from chemistry to describe the abrupt molecular change from solid to liquid, or liquid to gas, was the emergence of humanism, a new ethic that viewed the individual as important. The arts and sciences were valued as inherently worthwhile in their own right. Creativity was unleashed. The inventive power of Brunelleschi's "modern" urban architecture was one of many examples of public art and architecture that physically affirmed the transition.

During visits to Santa Fe Institute conferences, Padgett recognized a harmony between his analysis of 15th century Florence and Fontana's molecules reacting in solution. Fontana, a research professor in residence at SFI and an associate professor of theoretical chemistry at the University of Vienna, describes Padgett as an "intuition pump." When Padgett and Fontana discuss each other's research, creative ideas come forth like ripe fruit from the garden of the Badia at Fiesole.

"One of the unifying themes of interest to economists, physicists, biologists, and immunologists at the Institute is understanding the origin of novelty," says Fontana. "John brings an important social science perspective on the mechanics of novelty that escapes our formalization." For example, although the laws of physics don't change, the world churns with novelty. Padgett and his colleagues find evidence that change of social rules themselves gives rise to novel social and political structures.

Padgett is himself a product of the collisions of politics, civil rights, and foreign policy in 1960s America. He grew up in Waldorf, Maryland, at that time a rural tobacco and crabbing community of 2,000 residents. When he played baseball as a child, Waldorf Little League was still segregated. Padgett's own family tree has Catholic and Protestant branches and English, French, and Irish roots. He was valedictorian and president of his senior class of 50 at Ryken High School, a male-only parochial school.

His life embodied the nation's uneasy search for a new social order and political equality after the tumultuous 1960s. Like many of his high school classmates, he aspired to engineering. During summers while studying engineering at Princeton University he helped build the sonar systems for Poseidon submarines at the Norfolk Naval Shipyard. But later he was tear-gassed at Fort Dix, New Jersey, while protesting the war in Vietnam. "I got an electrical engineering degree, but I lost the faith," he says, grinning and leaning back in his university-issue office chair.

Padgett gravitated to political engineering. He was deeply influenced by what some might call the messiness of politics while working as a policy aide to Trenton, New Jersey, Mayor Art Holland in the mid-1970s. Holland, himself a former Jesuit priest, wanted to reform taxes that favored the rich. The mayor also wanted to erase zoning rules that effectively kept minority families out of white enclaves. He was impressed with Padgett's mathematical and analytical skills and solicited his help. But Padgett soon realized that no matter how well reasoned his proposed reforms appeared on paper, the mayor used a different calculus. Votes mattered. The opinions of political pals and the political debts owed them mattered. The mayor listened to Trenton's minority leaders. "After I would give a presentation to one of these groups, and invariably a Romanian lady would pinch my cheek and say, 'Such a nice boy,' I got a deep sense that social engineering is not how cities work."

The increasingly pragmatic Padgett realized that the real world was rarely reducible to conventional social or mathematical analysis. "When it came down to taking action, the mayor had all kinds of other constraints," Padgett says. "I couldn't put it into a computer and crunch it." Nobody could. "This had a big impact on me." He left Trenton for graduate school. After studying federal budgetary processes and earning a Ph.D. in political science from the University of Michigan, Padgett began to formally dissect interpersonal relationships and networks. "I do social network analysis," he says. Those networks include political, economic, and personal connections that extend from the neighborhood to the state and even influence how individuals create their own sense of identity. "How do crises reshape each network and how do they fit together over time?" he asks rhetorically. With that, he pencils a rough answer: It is a series of one-inch arrows arranged in rows, stacked on top of one another. The position of each arrow, the direction that it points, and which arrows it points to is a metaphoric representation of his analysis. Leading up to the Renaissance, the arrows are synchronous. They behave as if they were a perfectly choreographed school of fish. A downward pointing arrow could represent the tactic of one high-ranking family's policy of marrying "down" its daughters (to sons of lower-ranking families), thereby preserving social harmony. This intermarriage logic was common in Medieval Florence. But the Renaissance coincided with an abrupt change in the intermarriage conventions. The marriage arrows no longer point in the same directions. They swivel, become more chaotic, and lose cohesion. The school of fish scatters.

Padgett's arrows take increasingly complicated flights in the 15th century. And many of them point to and from the Medici family. "The Medici were like FDR (President Franklin Delano Roosevelt): They made alliances across trades and classes and across the city," he says. "The Renaissance was a particularly potent historical time for such novel institutional and personal inventions. I am trying to understand what actually happened in late Medieval marriage, economic, and political networks that induced such creative effects."

Padgett's analysis may change the way historians think about the forces that underlie new social and political systems. It also gives biologists another way to imagine how evolution, in a general sense, may operate to give rise to new species. How might his notions about the generation of novelty affect everyday life? Nobody knows. However, in theory, catalysts for change might be more thoughtfully designed; or useful institutions might be made to flourish with specific legal, social, or legislative changes.

Rex Graham is a senior editor at
Astronomy Magazine
in Milwaukee, Wisconsin

Anonymous.
Festival in the Piazza della Signoria, Florence.

SCALLA/ART RESOURCE, NY

Culture Group Meeting:

Agent-Based Modeling of Small-Scale Societies

Can we fully understand change in human affairs from the perspectives of the thematic disciplines? Philosophers (for millennia), anthropologists and geographers (for little more than a century) have said "no," and have attempted to view human phenomena as a totality. Anthropology at its best integrates human biology, cultural anthropology or ethnology, psychological anthropology, linguistics, and archaeology. But the task is daunting, and has led often to elegant, but very specific case studies. However, new theoretical approaches to adaptive systems and to modeling such approaches give hope that rigorous general formulations are possible.

The Culture Group at SFI focuses primarily on long-term stability and transformation in cultural developments. In December 1997, with the support of a grant from the Wenner-Gren Foundation for Anthropological Research to organizers Tim Kohler and George Gumerman, a diverse group of researchers gathered in Santa Fe to assess the progress of this working group and to chart future directions. Many fruitful exchanges ensued, ranging from general theoretical problems of cultural change and its explanation to the specifics of modeling actual cultural processes. Breakthroughs in modeling small-community networks in southwestern North America provided a touchstone for the discussions.

The American Southwest provides a unique arena for developing and evaluating models of small-scale societies. Over the last century, the peoples of living native communities in the Southwest have taught anthropologists about many aspects of their lives in this beautiful, varied, and often dangerous land. Archaeologists, geoarchaeologists, paleoethnobotanists, dendrochronologists, and many other scientists have constructed the most precise chronological sequences and cultural understandings available for any prehistoric culture anywhere. We know that between A.D. 200 and 1500, the ancestral Pueblo peoples took up increasingly intensive horticulture and more effective long-term food storage techniques. The also developed larger set-

tlements and more elaborate ceremonial systems. However, they periodically faced crises, abandoning large areas of the Southwest. Explicating growth, transformation, and crisis is a challenge to both theorists and model-builders. The construction of "artificial societies"—discussed as a general approach at the outset of the workshop by both Tim Kohler (Washington State U.) and Nigel Gilbert (Surrey, UK)—is proving increasingly productive.

A model in which the agents are households which can grow, fission, make adaptive choices about production and storage, make choices to move (perhaps joining other households) and, in the worst circumstances, fail, should generate the periodic aggregation into larger communities followed by abandonment that archaeologists can document in Puebloan prehistory. The team of George Gumerman and Jeff Dean (U. Arizona) working with Josh Epstein, Rob Axtell, and Miles Parker (Brookings Institute) and Alan Swedland, an anthropological demographer (U. Mass. at Amherst), designed such a model, inspired by the Brookings "Sugarscape" model. It represents households in the relatively small Long House Valley in northeastern Arizona from AD 400 to 1400. The households respond to known annual rainfall and potential garden productivity, documented by dendroclimatology and geomorphology, resulting in a sequence of settlement trajectories recorded in maps, which are comparable to those produced by archaeological survey.

The team of Tim Kohler and Carla Van West (Statistical Research Inc.) has been developing a model of adaptive choices by households in southwestern Colorado from A.D. 900 to 1300. They have built a Swarm-based model designed by Eric Carr and Jim Kresl with the help of Chris Langton which represents household decision-making in a similar way, but in a large geographical space.

In the previous year's meeting of the Culture Group, earlier versions of both models had provided impressive representations of growth phase, but had failed to show expected responses to environmental changes. However, this year the group was excited to learn that changes in agricultural variables suggested by several of last year's participants had produced responses to environmental change within the range of the archaeologically documented responses. Both teams are now ready to elaborate their baseline models by building in representations of such important processes as exchange, alliance building, and conflict.

The models developed for the Southwest and evaluated with the rich data of Puebloan life will be useful in understanding similar developments in other areas of the world. For example, 40 years of detailed anthropological research in highland New Guinea have built an even more detailed, albeit shorter, record which can be modeled in the same terms used for Southwestern communities. Archaeologists and dendrochronologists in the lake district of southern Germany, Switzerland, and adjacent France are building as rich a record of village societies of the fourth and third millennia B.C. as that from the Southwest, amenable to the same approaches. New work has just begun on the modeling of household decision-making in the early Holocene environments of the first farming villages in the hills of the Levant during the ninth and eight millennia B.C.—work which will borrow some of the approaches developed in the Southwest.

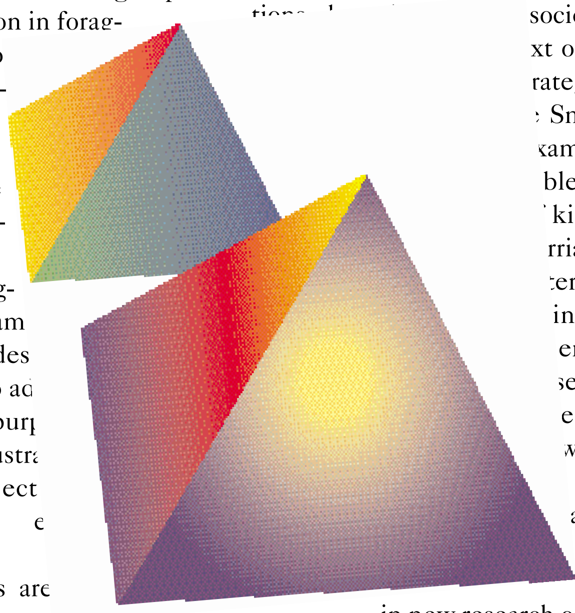
TAOS PUEBLO PHOTO: WILLIAM CLARK

ILLUSTRATION: PATRICK MCKELVEY

BACK TO THE BASICS: MODELING FORAGERS

Even as new applications are stretching our extant understandings of small communities, some workshop participants are working on both non-human primate foraging and pre-agricultural foraging groups. Renè te Boekhorst (Zurich) in a paper with Charlotte Hemelrijk discussed primate societies, specifically the theoretical issues of representing the nonlinear relations between group decisions about foraging for resources and individual decisions about relations with other individuals. Brian Skyrms (Caltech) presented the very different theoretical problem of generating simple systems of meaning and communication in the adaptive contexts faced by non-human primate foragers, specifically how more complex language functions might be generated from simpler calls.

In an impressive example of the modeling of forager strategies in such types of spaces as savanna, gallery forest and mixed environments, Stephen Lansing (U. Michigan) presented a model by John Pepper, Barbara Smuts and himself using a Swarm platform. This portrays foraging activities by primates and the consequences of such foraging for within-group selection and between-group selection in foraging groups. The model presently fo on foraging plant foods, but scavenging and hunting, and issues of developing communication systems as outlined by Skyrms could be added in future phases of development.



Those modeling specific foraging and food-processing behaviors am human foragers have several decades experience, and they have learned to ac a variety of extant software to their pur es. Mark Lake (Reading, UK) illustr such an approach with his project Mesolithic hunter-gatherers in e Holocene Scotland.

One of the few efforts in this are modeling to successfully evolve plant manipulation and domestication from a context of simple foraging is the Oaxaca modeling project of Kent Flannery (U. Michigan) and Robert Reynolds (Wayne State U.). Beginning with an overview of early Holocene foragers in central Oaxaca in southern Mexico, Reynolds described the use of "cultural algorithms," representing cultural knowledge or schemata, which could encode selected plant knowledge, presented in their book *Gulia Naquitz*. Under specified adaptive circumstances, their model generates emergent patterns of plant manipulation leading toward domestication, well beyond normal forager repertoires. Reynolds also touched briefly upon the new work of Flannery and himself in modeling the growth of political hierarchies.

MODELING HIERARCHICAL COMPLEXITY

Other workshop participants are working on more complex cultural developments. In considering the problems of evolving socio-political hierarchy, the workshop was fortunate to benefit from Jim Doran's years of experience in the abstract modeling of hierarchy in simple "artificial societies." Doran (Essex, UK) challenged the group to make explicit our tacit assumptions about "agents," "events," "knowledge," "rationality" and "cause." He urged the group to question the ultimate objectives of modeling, and to consider using models to generate sets of trajectories or "world histories" and look at the properties of these sets, rather than seek to replicate a single trajectory that happened to occur.

As the group's experience with simpler autonomous communities of foragers and farmers shows, researchers are most likely to question assump- societies, and to generate new xt of specific modeling efforts. rategy of chiefs in the Tongan Small (Arizona State U.) is a xample. Using a C+ platform, ble to represent actors in a kin relations, to apply strate- rriage, and to generate emer- terns of social status differ- in Polynesian chiefdoms. embedding this model in a sentation of a geographical e remains to be done, a way ward is certainly clear.

The final formal presentation was by Mark Lehner (Chicago, AERA Inc.), the Egyptologist most active in new research on Egyptian civilization during the third millennium B.C. Giving us some sense of the richness of extant knowledge of Old and Middle Kingdom lifeways, Lehner made a plea for complexity-based perspectives, and warned of the dangers of moving too fast into the modeling of complex cultural phenomena such as the Nile Valley in the Pyramid Age.

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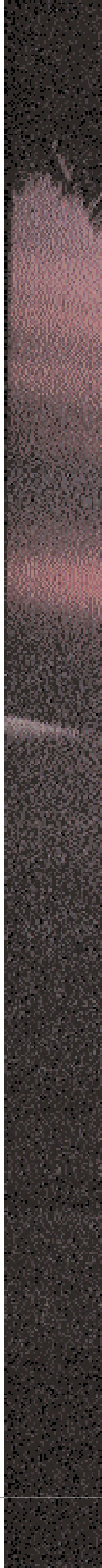


PHOTO: HENRY WRIGHT

WORKS IN PROGRESS

FRUITFUL DIRECTIONS IN THEORY BUILDING

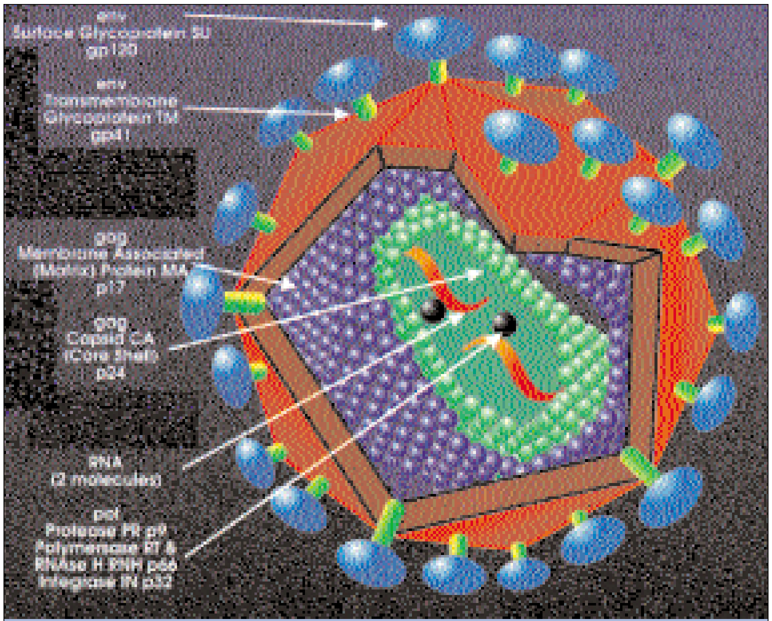
As in all successful workshops, some of the most promising advances were unplanned and unexpected. For example, in talking to Andy Wuensche of the SFI community, Steve Lansing found a solution to long-standing problems of how selection favors certain sets of behavioral rules, specifically rules for irrigation management on the Indonesian island of Bali, studied in his book, *Priests and Programmers*. Some of Wuensche's "random binary networks" behave like observed decision-making processes in Balinese agriculture.

The workshop ended with wide-ranging discussion of what the Culture Group should do to nurture the promising initiatives generated during the event. While there is much interest in Swarm as a platform for future efforts—particularly as it grows to incorporate new capacities to represent "cultural algorithms" and other symbolic elements—there was also discussion of the value of continuing to model with a diversity of platforms. Participants also generally agreed that a key challenge will be to learn to "grow" more complex systems from the simpler ones which had been the focus in this workshop, but that this should not be the exclusive focus of the Culture Group. Primatologists such as Smuts and te Boekhorst, linguists and philosophers such as Skyrms, and cultural anthropologists such as Lansing and Small could make vital contributions to the understanding of concepts, including "culture" itself, as well as to the specifics of both simpler and more complex case studies. Finally, recognizing the complexity of the human career, the group agreed that its members, and the Institute community as a whole, have an obligation to contribute to the building of human responses to global change.

HIV Dynamics and Evolution

Interactions between different scientific disciplines can sometimes result in unexpected and inspiring insights. In the past few years, this has been convincingly illustrated in the field of HIV research, where the application of mathematical techniques to biological data has shed revealing light on fundamental questions about the interaction between the virus and the host. While evolutionary biologists have been employing mathematical and statistical tools to study patterns in HIV sequence diversity for much longer, the first highly visible success of the combination of the two fields was the simultaneous publication in 1995 of two studies of the dynamics of virus and host cells (1).

Both studies were based on measurements of the response to potent anti-retroviral drugs. Since these drugs are able to halt the production of virus almost completely, it was possible to calculate how many viruses are produced and destroyed per day, how many CD4 cells are infected, and how many are killed. These studies represented an early and very successful attempt to employ mathematics to study the behavior of HIV, and their impact was profound.



The structure of the Human Immunodeficiency Virus (HIV) is relatively simple. The viral core contains the genome, or genetic material, which is accompanied by several enzymes essential to successful reproduction. Surrounding this in turn is the matrix protein membrane. Finally, encasing all these elements, is the viral envelope, which is composed of lipids taken from the host cell. Protruding

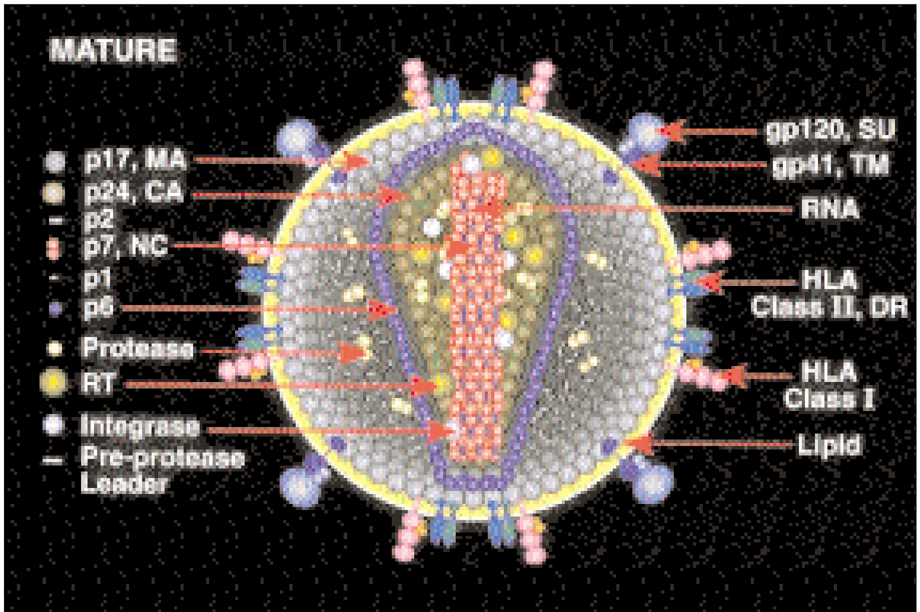
IMAGES COURTESY OF THE NATIONAL INSTITUTE FOR BIOLOGICAL STANDARDS AND CONTROL, UNITED KINGDOM

The collaboration between mathematicians and biologists has been encouraged by a series of annual meetings specifically intended to bring the two groups together. The fifth such gathering, HIV Dynamics and Evolution, was hosted by the Santa Fe Institute in April. About 150 participants focused on a wide range of topics, from global variation in the virus to the evolution of drug resistance, and from abstract models to analysis of recent data on the virus and the effect of drug treatments.

The application of mathematical models to HIV data has resulted in a steady stream of studies, which have led to better understanding and prediction of the behavior of the virus and the immune system, and have helped clinicians in making the very complex choices involved in treating HIV-infected patients. Subjects that are presently being studied include (among many others): what drug regimens are best to prevent drug resistance, given the virus type and the history of the patient; what are the dynamics of the virus-target cell interaction; which factors are most important for the killing of infected cells; what is the size, type and life span of the reservoir of latently infected cells; and under what conditions is it reasonable to assume that the infection has been cleared, and to attempt to discontinue drug therapy?

Another field where mathematics and biology touch is molecular evolution—the determination of the ancestry of HIV, and the estimation of its rate of evolution. The hierarchical classification of HIV into types, groups, and subtypes has changed a lot since the virus was discovered, and newly discovered variants continue to shed new light on its origin and family relations. Frequent recombination complicates all attempts at classification. Still, the classification is important for some lines of research, such as epidemiological tracking and vaccine design, so work is ongoing to attempt to adapt the classification to incorporate these variants.

The more subtle effects of slowing or stopping viral replication are only now becoming clear, and they frequently shed new light (and lead to new questions) on the nature of the infection itself. The numbers of infected cells, virions, and uninfected target cells appear to be mutually dependent in complex and unexpected ways. Upon infection, they reach an equilibrium in the host, the breakdown of which heralds the onset of AIDS. It is unknown what regulates this equilibrium, and whether the limitation on viral expansion is due mostly to immune pressure or to target cell depletion. This issue obviously is of paramount importance to the production of a vaccine. It is also still unclear why the equilibrium eventually breaks down. It has been found recently that the viral load is correlated with the turnover (production and killing) of infected cells. The mechanism for this is once again under debate. In all these issues, dynamic modeling plays an important exploratory and confirmatory role.



Detailed structure of mature HIV-1 virion.

Since the viral replication under Highly Active Anti-Retroviral Therapy (HAART) is almost or completely halted, the virus is also unable to generate mutants that are resistant to these drugs. This was clearly shown in a set of six patients, one of whom did not respond to therapy; in this patient, the viral DNA had changed profoundly over two years, while in the patients that did respond to the treatment, virus that could be found was unchanged, and not evolving. Since the generation of escape mutants is very difficult under these circumstances, some researchers argue that any escape mutants that do appear must have been present in the patient before the onset of the therapy.

Previously, the primary window into the viral evolution and dynamics within the host was blood samples, even though it was clear that the blood only contains a tiny (less than 10%), non-representative fraction of the total virus population. New experimental data have recently been obtained on the numbers of infected cells, virions, and target cells in the rest of the body; these data are now being used to refine the existing models of the dynamics of HIV infection.

The hope is that if viral replication can be suppressed for long enough by HAART, even the long-lived reservoir of HIV-infected cells will be emptied and the infection will effectively disappear. The life span of these latently infected cells is not known; according to some estimates, it could be as long as 20 years. It might be possible to speed up this process by "flushing out" the latently infected cells by forcing them to start replicating, which makes them visible to the immune system, but this requires a potentially dangerous treatment with uncertain outcome.

The broad range of new subjects presented and discussed at this conference suggest that many new and thought-provoking results can be expected from the synergistic application of biological and mathematical ideas and techniques to HIV research. The limits of this prolific field do not appear to be in sight yet, and the planning for the 1999 conference has already started.

Carla Kuiken

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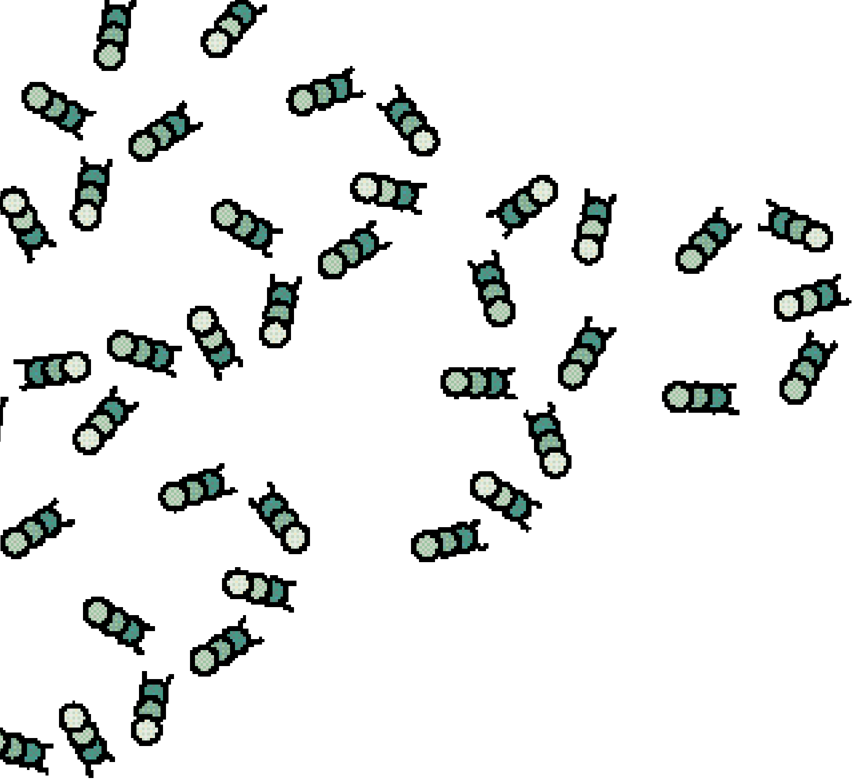


Swarmfest '98

Seventy-five researchers from diverse disciplines, but with a common interest in multi-agent modeling using Swarm, gathered at Swarmfest '98 this spring in Santa Fe. The aim of the conference was two-fold: to create a multidisciplinary environment where attendees could hear what is going on in other fields and pick up lessons they can apply in their own work, and to discuss among the user community the future direction of Swarm development.

INDIVIDUAL-BASED MODELING OF BACTERIA

Jan-Ulrich Kreft (U. Wales) led off the meeting with a presentation of his research in microbial ecology. His model of bacterial colony growth helps explain how bacteria make a living in the world.

"Bacteria do not usually grow in isolation," Kreft noted. "They are found in clusters where nutritional and social interactions are paramount." The early results of his model in Swarm show a dynamic group of cells of the same species with numerous interactions and activities. The bacteria self-organize into clusters; at high sugar density the clustering is symmetric and uniform. At lower sugar densities the clustering is asymmetric and perhaps fractal.

ORSCAPES: PLAYING WITH
E

Melissa Savage (U. California at Los Angeles) nstrated Arborscapes, a Swarm-based ecological l of forest dynamics. Arborscapes examines the f disturbance on species and landscape structure. ulated forest of 10,000 trees of up to eight differecies is hit by lightning strikes.

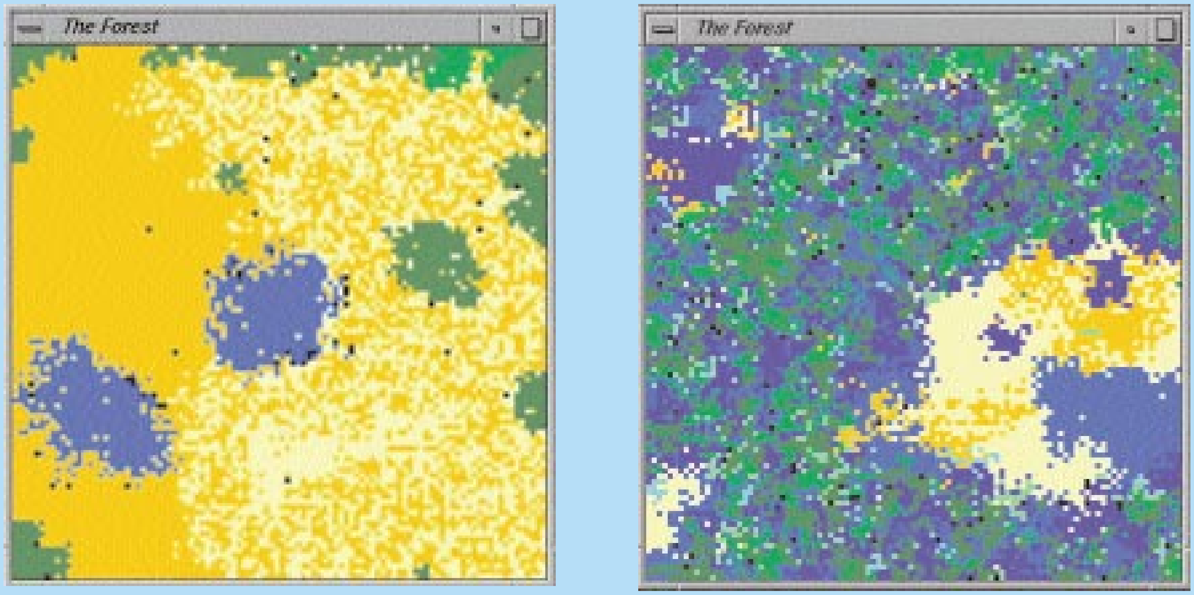
The initial goal of the model was to come up with retical analysis of disturbance dynamics and emerproperties based on local interactions on a spatialplicit landscape. The results of the simulation that the forest model does indeed obey a disturtheory that predicts the most forest ecology diverhen disturbances are at medium frequency.

The forest model displays some general properties of complex adaptive systems, such as sensitivity to initial conditions and behavioral basins of attraction. The next steps are to add topography, hydrology, blister rust, fire, beetle infestation, wind, and Geographic Information Systems (GIS) data to the model, and to incorporate the spatial analysis package, Fragstats.

MODELING INFORMATION WARFARE EFFECTS ON INFORMATION OPERATION

Paul Girard and Deirdre Poeltler of SAIC (Science Applications International Corporation) presented a prototype of an information warfare simulation. The simulation, incorporating both systems analysis and risk-assessment, is a training vehicle for information operations officers. The model features a hard-wired network of eight nodes whose capacities may become damaged by virus attacks or functional damage. In the simulation, friendly agents traverse and act upon the network while enemy agents seek to enter nodes and, if successful, steal or corrupt information.

Students, presented with the data provided by their respective agents, learn to assess and react to simulated attacks on information networks. The task is complicated by the fact that the data may have been subverted by enemy agents. Future development will scale the model up to 100 nodes, adding a greater diversity of agents and incorporating social agents who are capable of influencing and subverting enemy agents.



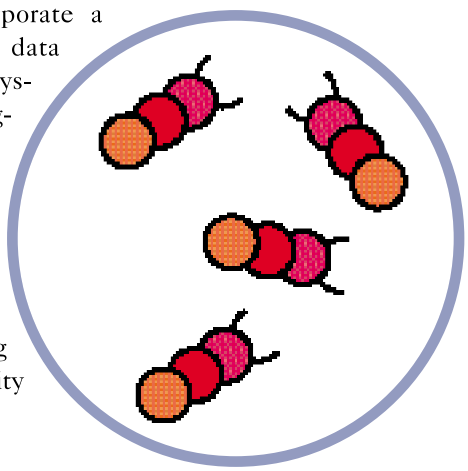
Arborscapes model landscapes of forest recovery from disturbance. A spectrum of tree species with varying adaptations to fire are represented across a successional spectrum: highly fire-adapted species (yellow), moderately-adapted (blue), and fire-resistant (green). In the left scene, a high disturbance regime causes the forest to oscillate between landscape-scale burns and colonization by fire-adapted species, threatening clusters of resistant species. In the right scene, a moderate disturbance regime results in spatial heterogeneity and higher species diversity.

FUTURE DIRECTIONS

The greatest need according to the user community is to make Swarm easier to use and more accessible. The Swarm developers are already working to improve Swarm's utility by making the documentation of the system integrated with the current codebase. Swarm 1.2, just released, includes complete indicies to all functions and protocols. Production of a user guide and more fully-documented examples are also on the future agenda, along with plans to offer multi-language support permitting users to write Swarm simulations in the programming language of their choice.

Swarmfest users also want to write larger and more complex Swarm models. There are two ways to accommodate larger models. In the current implementation, the existing code will be optimized to improve the efficiency of memory usage and provide speed-ups at runtime. A future plan is to support loosely-coupled parallelization in which models could be distributed across several machines.

To facilitate the incorporation of real-world data into Swarm simulations, Geographic Information Systems will be used. These are databases containing massive amounts of geographic and spatial data. Some Swarm simulations are based on abstract landscapes and environments; other Swarm models consist of agents interacting on actual geographic data. To facilitate the incorporation of real-world data into Swarm Simulations, Swarm developers are researching the technologies required to incorporate a transparent exchange of data between Swarm and GIS systems in the medium to long-term future.



Further Swarm enhancements also being contemplated are improved facilities to run multiple experiments beyond the existing parameter sweeping and batch mode functionality

Ultimate Causes and Proximate Determinants of Animal Sociality

The aim of this January workshop coordinated by SFI postdoctoral fellow Eric Bonabeau was to ask basic questions about evolution and behavior in the context of animal sociality. (The interactions of social insects or communal breeding animals are good examples of animal sociality.)

Kin selection is certainly a beautiful and powerful framework in which to discuss the evolution of social traits, but consideration of behavior, also an important part of this framework, is frequently neglected. What happens if behavior is taken into account? More precisely, one may ask the following questions:

Are there attractors in evolution, in particular social attractors (that is, attractors towards a certain type of social organization), such that going back to solitary behavior would require large correlated mutations? This points to the question of the origin and maintenance of sociality, from communal animals to the most highly socialized species, those who are "eusocial." Eusocial animals feature overlapping generations, cooperative brood care, and, most importantly, the reproductive division of labor. For some individuals, participation in communal life requires the "ultimate" sacrifice, loss of reproductive potential. How did eusociality emerge, and why is it so stable? Are the various steps towards "highly eusocial" species a series of convergences towards deeper attractors? How stable and robust are these attractors? Can social attractors be generically robust to mutations (canalization)?

In summary, how are strategies predicted by evolutionary theories behaviorally implemented? Such strategies may involve extremely complicated decisions (such as, for example, in parental investment). How can such strategies be approximated at the level of individual behavior?

Further summarizing, what is the role of self-organizing mechanisms in the origin and maintenance of (eu)sociality? Can various types of self-organizing mechanisms explain attraction towards eusociality? How does behavioral self-organization interact with evolution? Self-organization, combined with appropriate genetic and environmental constraints, can explain a lot about collective behavior in social insects without invoking individual complexity. By connecting individual and colony levels without resorting to complex individuals, can we hope to clarify the origin of collective behavior, from both the proximate and ultimate viewpoints?

TOP: Cooperative leaf folding in weaver ants.

PHOTOS: GUY THERAULAZ

In a series of formal presentations interleaved with discussion, participants addressed these issues. The first morning was devoted to the interplay between phenotypes and evolution, particularly social phenotypes. Afternoon talks were about sex ratios, a particularly important aspect of social evolution. New experiments seem to confirm more and more subtle aspects of kin selection within the context of sex ratios. The next day was entirely devoted to self-organization and colony organization in social insects. The third morning was dedicated to social behavior in birds and mammals, as was the fourth morning. Game theory was also represented in this fourth morning. The afternoon was devoted to regulatory networks. The last morning was entirely dedicated to discussion, with two formal talks summarizing the workshop.

According to Bonabeau, the main achievement of the workshop was consensus among some of the most prominent researchers in the field of behavioral ecology about the importance of including self-organization in studies of the evolution of social behavior. He notes, "These researchers were more than skeptical on the first day, and were pretty much convinced when they left. A phase transition took place on the evening of the fourth day that I still do not fully understand. The impact of this phase transition must not be underestimated; not only have the scientists moved toward accepting self-organization as a major concept to explain collective behavior in animal societies, they also admit that it may alter in fundamental ways the way we think about evolution in general."

Bonabeau continues, "Although developmental biology was not the topic of the workshop, many participants felt that the very same concepts, borrowed from self-organization, apply to development and are essential in the understanding of evolution. Seeing sociogenesis as a developmental process seems to be a fruitful metaphor."

Research growing out of this meeting can be developed along three lines: the evolution of social behavior, developmental biology, and self-organization in artificial evolution. Each of these topics relates to work now being done at the Institute. SFI's expertise in self-organization and complex adaptive systems should give the research a head start, but the question of how self-organization interacts with evolution still remains to be determined.

SFI FOUNDING MEMBER, RICHARD SLANSKY 1940-1998

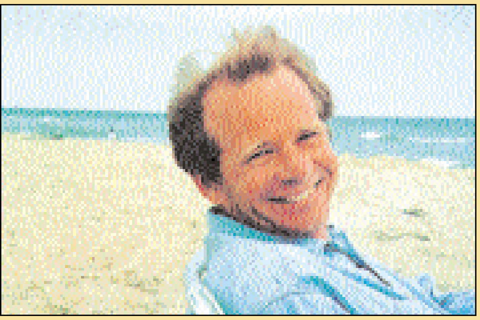


PHOTO: MARY MOSS GREENBAUM

Richard Slansky, a founding member of SFI and director of the Theoretical Division at Los Alamos National Laboratory (LANL), died in January at the age of 57.

Slansky, well-known for his contributions to theoretical physics, published 85 scientific papers and served as editor of the journal *Physics Reports*. He gained international recognition for his work on the application of the mathematics of group theory to unified theories of all the basic laws of nature.

Slansky received his bachelor's degree from Harvard University and his Ph.D. in physics from the University of California at Berkeley. He served on the faculty at Yale University before joining the Theoretical High Energy Physics Group at Los Alamos in 1984.

He arrived at LANL just as the initial, informal discussions were beginning that led to the founding of SFI, and Slansky was an active participant from the beginning. "They knew I was interested in interdisciplinary problems," he recalled during an SFI interview in 1994, "and I was invited to sit in." Slansky helped organize the founding workshops at the Institute and served on the Science Board. As director of the Theoretical Division at LANL, he encouraged interactions between the two organizations. "We have a number of people in the Theoretical Division who are involved at the Santa Fe Institute," he said in the same interview. "I think the broadening of scientific interaction is really important."

The SFI community recalls Dick Slansky as a superb scientist and strong supporter; he is also remembered as an avid skier, hiker and river runner as well as an accomplished pianist and lover of music.

EBLE JOINS RESEARCH STAFF—SFI AND SMITHSONIAN INSTITUTE TEAM UP TO STUDY EVOLUTION

PHOTO: MYLE DUCHARME

Gunther Eble joined the SFI research staff as a postdoctoral fellow last fall although he will not actually take up full-time residence at the Institute until this fall. Eble's fellowship is jointly sponsored by SFI and the Smithsonian Institution, and he spent the first months of his appointment at the Washington D.C. organization.

Eble received his doctoral degree in evolutionary biology at the University of Chicago in 1997. He is investigating one of the major themes in evolutionary biology: what governs the evolution of form over long time-scales. Evolutionary innovations in body architecture (the form and structure of an organism) do not arise continuously or randomly over geological history, but are concentrated in particular time intervals, lineages, and habitats. The constraints on why certain evolutionary directions are not followed are as important, and as elusive, as the new directions themselves.

Using paleobiology and evolutionary biology as a springboard, Eble is looking in general at models of origination and their testing with extensive historical records. He'll bring to this project his continuing empirical work on sea urchin evolution. He views this dynamic as a model system where a long history and excellent fossil record allow many issues to be investigated quantitatively.

TRANSITIONS

"excellent, transdisciplinary, fresh, and catalytic"

Integrative Themes

Erica Jen

One of our less modest, but nonetheless oft-stated, goals at SFI is to support a new kind of research community in carrying out research that is, to quote from the "Vision Statement" drafted in 1994 by our Trustees, "excellent, transdisciplinary, fresh, and catalytic." What this means, among other things, is that we try to bring researchers together to dialog, and especially to step out of their usual research modes and talk with other researchers representing disciplines and perspectives that they might usually regard as far afield.

PHOTO: WALTER NELSON

Another way to put it, somewhat more concretely, is that at this point in SFI's development, our goal is to bring the broadly defined scientific community together to address fundamental issues of simplicity and complexity in natural and social phenomena. Our approach relies heavily on achieving an integration between specificity and generality; this necessitates developing an understanding of specific natural and social phenomena in the richness of their details, and abstracting from these details fundamental principles of general complex adaptive systems.

It's fair to say that SFI works well when we are doing a good job at integration, and not so well when we are not. It's also clear that integration, and all the related aspects of building a new kind of community, require active effort on our part; they don't just happen naturally. Two of the research results that represent SFI at its best—the artificial stock model developed by Arthur, LeBaron, Holland, Palmer, and Weber; and the allometric scaling work by Brown, Enquist, and West—depended essentially for their development on a disciplined effort on the part of the collaborating researchers to merge their scientific agendas and perspectives. And those SFI workshops that managed to imbue participants with the desire to achieve integration—including the 1987 founding workshops and the 1992 workshop on "Common Themes of Complex Adaptive Systems"—have played a seminal role in charting SFI's intellectual course over the past 10 years.

With our history and goals in mind, we are scheduling an SFI integrative themes workshop to be held in July of 1998 in Santa Fe, NM. The workshop will span a two-week period, with participants in attendance for the full duration. Prior to the meeting, briefing reports from subsets of participants will be circulated for general review. The two weeks of the workshop will consist of presentations, discussions, and working group meetings. The tentative format is to structure the workshop around specific topics, with one day per topic in the first week for talks, working groups, and discussions, and a follow-up day in the second week on the same topic for additional talks and reports from the working groups. Participants at the workshop will include members of the SFI External Faculty as well as a small number of SFI Science Board members.

The decision to base the workshop around the SFI External Faculty was made in recognition of the central role played by these individuals in determining the current and future scientific agenda of the Institute. In the past, the role of External Faculty at SFI has not been so decisive. Early on, some thought that the Institute might grow eventually into an academic institution, with the usual accoutrements of a permanent faculty, accredited curricula, and degree-granting programs; in such a scenario, it isn't clear what being an External Faculty member would mean. In recent years, however, the Institute community has accepted that remaining a visiting institution is critical to maintaining an innovative nature, and that the External Faculty, in fact, constitutes the true scientific driving force of the Institute.

We expect that proceedings of the workshop—including both technical presentations and summaries of discussions—will appear as books to be published by Oxford University Press.

The topics to be discussed at the workshop include the following:

- Paradigms of interaction: causality, concurrency, and autonomy
- Learning in distributed systems
- Characteristics of systems capable of open-ended evolution
- Patterns of dynamics in co-evolving adaptive systems
- Decision-making in complex environments
- Resilience, phase transitions, and criticality
- Agent-based simulations
- Integration of various levels of complexity in a system

40th SFI Book Now In Print

Viral Regulatory Structures and Their Degeneracy by Gerald Myers presents the proceedings of a workshop held at the Santa Fe Institute that brought together researchers working on HIV and HPV structures. The two viruses, which are quite different in many respects, have some analogous strategies and molecular structures for interdicting cellular pathways, and it was these common threads that received the most attention during the workshop. Chapters of the book cover virus-cell interactions, regulatory proteins, nucleic acids, and the modeling of viral evolution.

Viral pathogenesis is clearly one of the difficult problems of our times for which multidisciplinary, synthetic investigations are needed. Both viruses are small tumor viruses with limited complexity in the form of a handful of virally-encoded regulatory elements. The book attempts to shed light upon the "similars among dissimilars." For example, both viruses encode so-called zinc-finger proteins that bind to DNA and proteins. To take another example, the Vpr protein of HIV has recently been shown to influence cell cycle progression, an event of central interest to HPV pathology. Not only do the two viruses interact with some of the same cellular pathways, they can interact with one another when present in the same cell. HIV tat protein enhances papillomavirus early gene expression, for example. Rarely will HIV and HPV be found in the same cell; however these interactions suggest that HIV-like molecules will affect HPV, and HPV-like molecules will affect HIV. In terms of scientific knowledge, many of the findings about one virus are unfamiliar to researchers working on the other viral system.

The book sells for $61 (cloth 0-201-32821-6) and $35 (paper 0-201-32822-4). To place an order, please call 1-800-822-6339. Tune into our website for publisher and order information, as well as new releases and upcoming volumes (http://www.santafe.edu/sfi/publications).

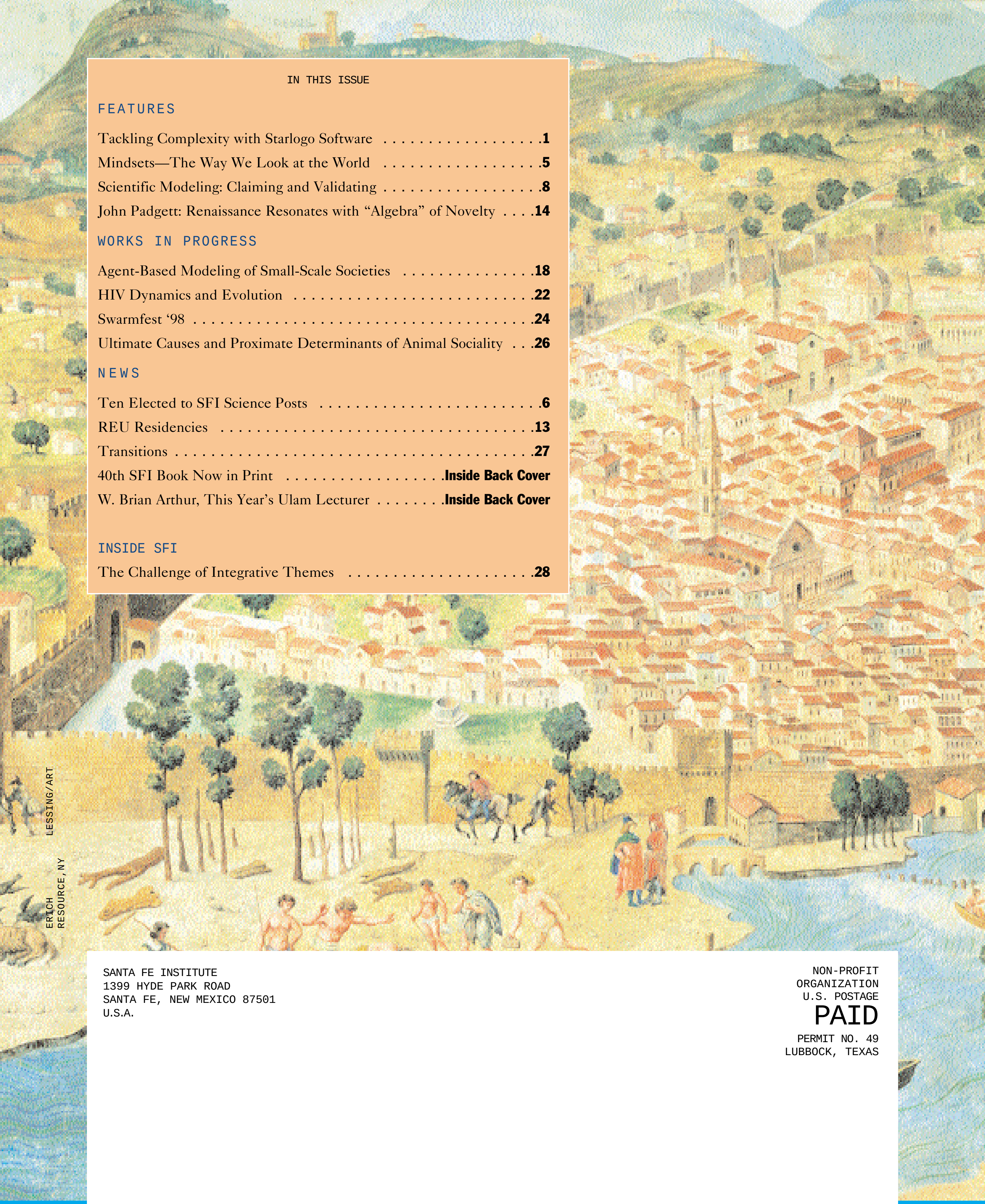
PHOTO: DAN BARSOTTI

W. BRIAN ARTHUR, THIS YEAR'S ULAM LECTURER

The Institute's annual Stanislas Ulam Lecture Series features a leading complexity science researcher discussing his or her cutting-edge work. On September 15, 16, and 17 at the James A. Little Theater, SFI Citibank Professor W. Brian Arthur will speak on "The New Economy"—three related talks for a general audience.

As this millennium gives way to the next, the economy is undergoing a deep change. It is shifting steadily away from the brute force of manufacturing into the forces of mind—from the processing of bulk materials into the processing of digital representations. This change has been much written about and much discussed in the press. In these three lectures, Arthur will argue that the new economy overturns our old understandings. It redefines products. It redefines markets. It creates new structures. The modernist interpretation of the economy fails. Standard economics no longer applies. And the new technologies paradoxically lead to a less mechanistic, more organic economy.

For a complete schedule of SFI's free community lectures in the fall, call 505-984-8800 or visit the Institute's home pages at http://www.santafe.edu.



ERICH LESSING/ART RESOURCE, NY

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