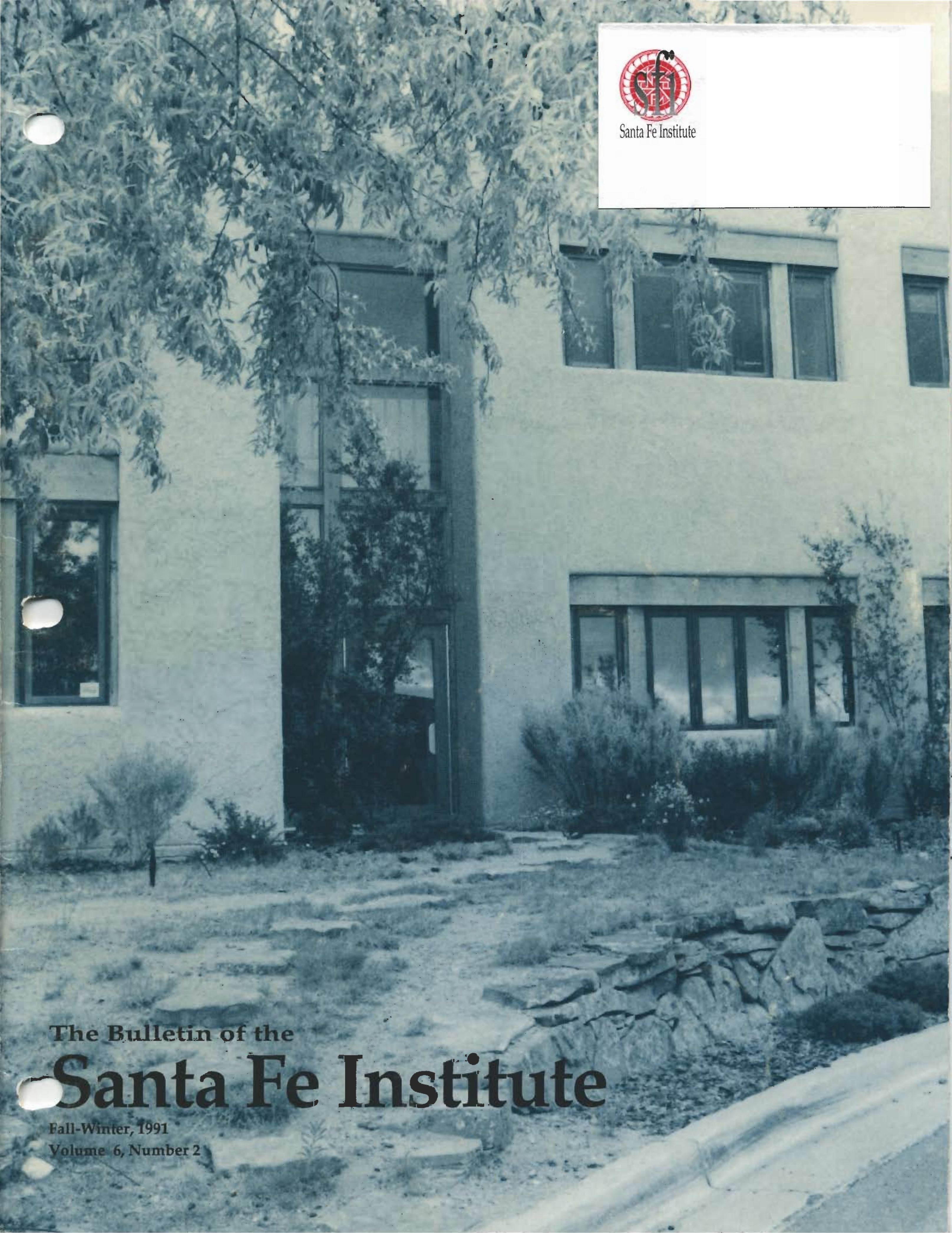
Santa Fe Institute



The Bulletin of the

Santa Fe Institute

Fall-Winter, 1991
Volume 6, Number 2

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Photograph of the new offices of the Santa Fe Institute in the Pecos Trail Office Compound; see article and map on page 23. Photo by Cary Herz © 1991.

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Santa Fe Institute

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The Santa Fe Institute is a private, independent organization dedicated to multi-disciplinary scientific research and graduate education in the natural, computational, and social sciences. The driving force behind its creation in 1984 was the need to understand those complex systems that shape human life and much of our immediate world—evolution, the learning process, the immune system, the world economy.

The intent is to make the new tools now being developed at the frontiers of the computational sciences and in the mathematics of nonlinear dynamics more readily available for research in the applied physical, biological, and social sciences.

The First Six Months

Edward A. Knapp. Photo courtesy of Los Alamos National Laboratory.

It gives me great pleasure to write this, my first President's Message, to the friends, supporters, and researchers associated with the Santa Fe Institute. In the six months since I became President of the Institute, I have been continuously amazed with the vitality and the strength of the research programs and networks which have been flourishing here in Santa Fe. The future looks bright indeed for research in the broad range of sciences which the Institute supports. Further on in this Bulletin, you will receive in great detail news of the various programs which we are undertaking. But let me spend a few moments with you going over the incredible variety and breadth of the emerging programs at the Institute today.

The oldest established program at the Institute is the one in economics, and we are hosting several important workshops in this program in the next few months. A workshop on "Growth in Cities" will be held in late September, and later in the Fall a meeting will be held jointly with the North American Institute on harmonizing economic competitiveness with environmental concerns. John Geanakoplos and Larry Gray describe their work on decision making in complex environments, page 4 of this Bulletin, work undertaken in the first half of this year.

An extremely exciting development at the Institute is the emergence of a new program which encompasses the development of the mathematics and computer simulation techniques necessary to model complex adaptive systems, an effort which we have dubbed adaptive computation. We have held a planning meeting for the program, and a founding workshop is scheduled for March, 1992. This program will bring together research on the tools necessary to model many of the global systems we are interested in, and it looks very promising as a major program at the Institute.

Somewhat behind the adaptive computation program but very active at the present time is planning for a program in the study of biological systems. Several areas in biology in which we have been quite active are suggested, including but not restricted to models of the immune system, applied molecular evolution, and studies in neurobiology.

This summer we hosted an extremely exciting workshop on "Paths to a Sustainable Society," which has led to the preparation of a proposal for a joint program on sustainability with the Brookings Institution and the World Resources Institute. In addition to this specific program, several members of the Institute are deeply interested in this topic and are pursuing portions of this very broad subject independently.

With so much action in new programs, one of the major worries of the Institute governance is how to pursue all of these directions simultaneously and still retains the broad general character of the Institute, the very reason for which it was founded. It is relatively easy to obtain support for narrow programs which match the research interests of the government agencies or foundations we deal with. It is much more difficult to obtain support for core research programs, those which bridge the disciplines and make the Institute unique. We will be concentrating on development goals which develop support for our broad integrating studies, as well as support for the individual studies described.

In other areas, the establishment of the journal *Complexity* has proceeded very successfully. Harold Morowitz has agreed to be Editor in Chief, and we are actively recruiting an executive editor. The journal will be published by Pergammon Press. Our publications series has continued to prosper, and we have several new volumes nearing completion. The working paper series has expanded dramatically; so far this year we have published 31 papers, and it could go as high as 60 by the end of the year.

I think the most gratifying result of our programs so far is the enthusiasm with which visiting scientists participate and then describe their experience at the Institute. It is almost overwhelming. Quotes like "the most stimulating intellectual experience of my scientific life" are common. We have had an attendee who had only heard of the Institute third hand come and spend a few weeks and then promise to return next year, offering to organize major workshops and help obtain funding for them. This coupled with the very "real world" nature of the problems we study is making the Institute a real force in the scientific arena. The world needs scientific answers to the kind of questions we are posing, such as the problem of sustainability, models of the operation of the human immune system, more reliable models for economic forecasting, understanding decision making in a variety of uncertain situations, and so on. The Santa Fe Institute brings the full range of scientific training to bear on these and related problems, with the best scientific talent the nation has to offer. In insisting on looking at the whole problem, the entire system rather than the component parts as is the rule in the disciplinary approach common in the university system, we hope to bring new insight into the solutions we obtain. In developing a bottoms-up system approach and observing the emergent behaviors of widely different complex adaptive systems, regularities may become apparent between the global behavior of different systems. These regularities may guide studies in widely unrelated problems. That is the hope and the promise of the Santa Fe Institute.

Ed Knapp

When Seeing Further is Not Seeing Better

By using games like chess as models for the process of making decisions in a complex world, we discover circumstances under which looking far ahead in a decision tree leads to poor choices. In particular we assert that the Shannon algorithm, which is the basis of most computer chess programs, is flawed because it does not take into account its own bounded rationality. We derive several meta-principles for decision making, and show that they explain some recent successful deviations from the Shannon algorithm. We conjecture that they will lead to other important modifications, or even a completely new algorithm.

A new machine has called into question our assumptions about calculation. Deep Thought, a chess-playing machine that can calculate more moves ahead than all other computer program, has taken first place in the World Computer Chess Championships, defeated a number of human grandmasters, and even challenged, albeit unsuccessfully, World Champion Gary Kasparov. Deep Thought's designers are working on an even more powerful microchip with which Deep Thought will be able to calculate an additional two full moves ahead, giving it enough strength (so they claim) to beat Kasparov with ease. Can we agree with Gary Kasparov, who still believes that brute calculation does not necessarily provide the best answers?

Because chess is a complex setting in which we cannot accurately quantify our ignorance, and in which the calculation of all possible consequences of an action is beyond the capabilities of any computer, even beyond those of any computer imaginable, we can use the game as a metaphor for studying decision making, learning, and expertise. At the Santa Fe Institute conference on Learning in Economics, Psychology, and Computer Science, held in January 1991, the game of chess was a frequent example in many of the discussions. As a consequence, the two of us began chatting about chess and computers, and John posed the following puzzle.

If computers could perfectly assess the value of a position in chess, they would not need to look ahead more than one move. On the other hand, if they are incapable of evaluating a position at all, it would do them no good to look ahead more than one move. Why is it then, that when their ability to evaluate positions lies somewhere between the two extremes, it seems to help them to look ahead as many moves as possible? One easy explanation is that positions become appreciably easier to evaluate as one goes deeper into the game. But can this be the whole story or even be right? After all, the typical foresight horizon of the strongest chess computer is only four or five moves, and who would argue that positions are on the average much simpler at move 15 in a game than they are at move 11? Of course, some positions are clarified by looking ahead, but at the same time, many simple positions have complicated successors further down the tree of moves. The more we talked, the more the puzzle grew, and we began to hunt for some general principles. The trail led us to some surprising discoveries, and a new project at the Santa Fe Institute emerged.

The question that we have raised applies to many situations besides chess, and indeed our project is not really about chess, but about decision making in complex environments. Imagine, for example, a traveler who needs to drive from downtown Manhattan to the Upper West Side of New York City. She is only vaguely familiar with the layout of the city, but she does have a detailed map. Using the map is difficult in traffic, and it is time-consuming to park somewhere for a closer look. Furthermore, the map is not completely clear about one-way streets, and says nothing at all about traffic jams, road construction, or stop lights. Should she try to trace out as much of the route on the map as can be reliably remembered, including all sorts of alternate routes to allow for unforeseen complications (i.e., look ahead as far as possible, keeping in mind that no one could retain a complete plan, allowing for all contingencies, in such a complex situation), or is it better to adopt a one-step look-ahead plan, such as always trying to head uptown and somewhat toward the west. Consider also a father facing a difficult decision about how to discipline a child. Should he try to calculate all the possible ways in which his child, and his other children, might react, and then how they subsequently might react to his reaction to their reaction? Or should he simply do what seems fair on general principles? One can easily find similar examples in a variety of other settings, from the worlds of economics and politics, to the affairs of the heart.

Are there rules, "meta-principles," prescribing when making choices based on general principles is superior to looking as far ahead as possible, and vice versa? If some calculating is to be done, are there meta-principles prescribing what to calculate? The Shannon algorithm for game play by computers, which we will describe below, is based on the belief that seeing further is seeing better, and so comes firmly down on the side of calculation at the deepest possible level in a decision tree. But when sight is cloudy at best (as is the case when a computer looks at any given chess position), is this belief justified? Since the Shannon algorithm does not make any allowance for its own imperfect vision, we think not, at least not all of the time. In fact, we have discovered several ways in which looking ahead can be misleading, as well as ways in which it can be helpful.

Of course, we are not the first to have noticed that looking far ahead is not always the best policy. But there appears to be very little systematic work on finding an alternative. Some people have tried to figure out why search depth has been so successful in practice, particularly for chess computer programs. But relative to the tremendous amount of effort put into hardware and software intended to help computers look ever deeper, there has been relatively little work directed at understanding the *failures* of search depth, and when such work has been done, the usual recommendation is to look even further ahead.

Information and information-processing considerations play an important role in economic theory, including capital theory, finance, macroeconomics, game theory, and labor theory. In all of these situations it is assumed that the agents are aware of their own limitations, and that they can quantify their ignorance. Across all of these decision problems, knowing more means doing better. Chess is a fascinating paradigm for decision making in complex environments precisely because, as in most real life situations, it is a setting in which we cannot accurately quantify our ignorance. We should therefore not be surprised if some natural decision-making routines do not have the property that they perform better when they are given more information. As we shall see, the Shannon algorithm is particularly vulnerable to this problem since it makes no attempt to compensate for its own fallibility.

A straightforward example in which learning more may be harmful is when there is "roundoff error," so that after sufficiently many calculations, the small errors inevitably made at each step accumulate and the final answer is almost certainly wrong. One sometimes sees this in chess, when a commentator on some game declares that a move is good (or bad), giving as proof a 15-move variation with "best" play by both sides. Although the evaluation of the final position in his variation may be unambiguous, and there may be no obvious blunder in the given line of play, the possibility that at each step there might have been a slightly better move leaves the conclusion still very much in doubt. (The Shannon algorithm searches exhaustively every possible move up to a certain depth, so it is not necessarily subject to this kind of error.)

In order to compensate for one's ignorance, it would seem necessary to quantify it, but how does one do that in a real-life setting like chess? In our project we propose to solve this dilemma by following a two-step plan: First we build a precise model in which the ignorance is quantified, and we derive mathematically the correct decision-making algorithm. Second, keeping in mind that such a model cannot be a faithful portrait of reality, we look for principles of decision making that are independent of the way in which we quantify ignorance.

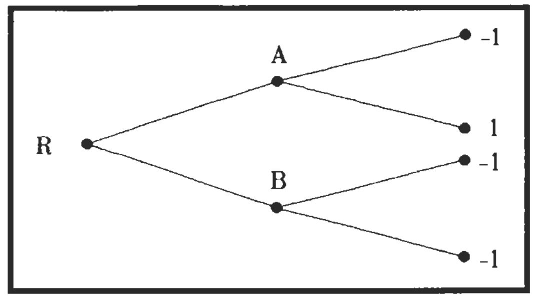


Figure 1: A two-stage decision tree.

A Simple Example

We illustrate some of the main ideas with an example. Imagine a person who must choose a course of action. The choice is to be made in two phases or moves, with two alternatives available at each move. Thus there are altogether four possible decision paths. Suppose that only one of the four paths is desirable. We depict the situation in Figure 1.

The black dots in the picture represent different points, or positions, that can be arrived at in the decision-making process. Positions on a tree of this sort are also called "nodes." The node labeled R is the starting point, or "root" of the decision tree. The two alternatives at the first move are labeled A and B. There are two further alternatives stemming from each of the nodes A and B. Of these, only one represents the desirable end result. This correct "terminal node" is labeled with a 1, and the remaining terminal nodes are labeled with –1's. We think of these numbers as the payoff to the decision maker for arriving at the corresponding positions. To achieve the payoff of 1, the person must first choose A, and then take the lower branch stemming from A. Any other path results in a payoff of –1. (A payoff of –1 means that the player loses 1.)

Note that once alternative B is chosen, it is not possible to reach any payoff higher than –1. Thus we may reasonably assign the value –1 to node B. On the other hand, it is possible to reach the payoff 1 from node A, so we assign the value 1 to node A. The values that we have assigned A and B are the highest possible values that can be reached from those nodes. Working back further, we may similarly assign the value 1 to the root node R.

We have illustrated a special case of a procedure, called "backward induction," by which we can systematically assign values to the nodes of any finite one-person decision tree, provided all of the terminal nodes have been assigned values. In general, to find the value of any node whose successors have already been assigned values, simply take the maximum of the values of its successors.

Continuing in this fashion, we can assign values, one level at a time, to all of the nodes, starting from the end of the tree and eventually reaching the root node.

Once we specify who moves at each node of the tree, backward induction also works for two-person decision trees in which the two persons (traditionally called "White" and "Black") compete against one another. Such a situation is often called a "game" (or more precisely, a "zero-sum game"). To find the value (to White) of any node whose successors have already been assigned values, take the maximum of the values of the successors if the node represents a position in which it is White's move, and if Black is on the move, take the *minimum* of the values of the successors. This is the so-called "min-max" procedure. Both it and the simpler "max" procedure used for the one-person situation work equally well when the terminal nodes have been assigned values other than 1's and –1's.

Once backward induction has been carried out, it is often useful to talk about decision paths along which the "best" choices are made by the people involved. To find such a path, start at the root node, and then choose at each successive node what is best for the player on the move; that is, choose the node that has been assigned the best value for that player. (If there is a tie, choose arbitrarily among the best nodes.) This procedure results in a sequence of nodes that we call an "intended path" or "intended line of play." In the computer chess literature, an intended path is also known as a "principal continuation."

For a finite game, such as chess, in which the outcome or payoff depends solely on the final position, backward induction implies that the strength of any intermediate position is entirely determined by the strengths of the positions that can be reached from it. This insight led the logician Zermelo in 1912 to prove that for chess, every position, including the starting position, must have a value (win for White, win for Black, or draw), representing the outcome that would inevitably result from best play by both players.

This kind of argument was implicitly familiar to the leading chess players of the 19th century. The concept of backward valuation had also been introduced into economics by the great Austrian economist Karl Menger in the 1870s. (He imputed value to productive machinery from the value of the consumption goods produced.) Wilhelm Steinitz, the first universally acclaimed world chess champion and the acknowledged father of positional chess, who incidentally lived in Vienna at the same time as Menger, took the argument one step further. He reasoned that the valuation of a position could sometimes be obtained from general principles, without any further calculation. To the extent that positional considerations lead to correct valuations, they must agree with the results of backward induction. As Emmanual Lasker, the mathematician who defeated Steinitz for the world title, put it, Steinitz's insight led to the death of the romantic school of chess. If it can be seen on purely positional grounds that White has at least a draw, there is no point in Black making long calculations to find a brilliant winning move. Until Black can see that White has made a mistake, no such move will be available.

Let us now return to our simple one-person, two-move example. Think of the tree in Figure 1 as the initial part of a much larger decision tree, with the values being the ones that would be arrived at by backward induction from the final nodes of the larger tree, *if such calculation were possible*. But suppose that such calculation is not possible. Instead, the decision maker is only capable of guessing at the values of each of the nodes in the smaller tree, basing his guesses on "positional principles." This is essentially the situation faced by the chess-playing computer. In the 1950s, the information theory pioneer Claude Shannon suggested an algorithm, combining the ideas of Zermelo and Steinitz, for how a choice should be made between A and B. According to Shannon, the decision maker should assume that his guesses for the values of the four terminal nodes of the tree in Figure 1 are the *actual* values of these nodes, assign values to A and B accordingly by backward induction, and then use those values to choose between A and B.

This is the Shannon algorithm with two-move lookahead. Of course Shannon realized that the guesses being made are likely to be wrong at least some of the time, and he suggested two ways in which the procedure could be improved. One way is to program more sophisticated positional principles into the computer, so that it can make better guesses. The second way is for the computer to look further ahead. In practice almost all of the improvement has apparently come from the second approach.

Our question is why this should help at all, at least when the later positions are as hard to evaluate as the earlier ones. In our example, let us assume that there is some probability p that the decision maker correctly guesses the value of a given position, so that with probability $q = 1 - p$, he guesses the wrong value. We also assume that the errors in these guesses are independent of one another. (By making these assumptions, we are implicitly eliminating the possibility that decisions are easier deeper in the tree.) Now comes a surprise: it turns out that, no matter what the terminal values, and no matter what the value of p for $1/2 \leq p \leq 1$, the decision maker would do better to look only one move ahead! (There is no point in considering values of p smaller than 1/2, since even a random guesser gets the value right half of the time).

As stated earlier, there are others who have noticed that the Shannon algorithm's ability to make a correct move diminishes with deeper search depth, at least when the error probability is the same for all positions. In a book called *Heuristics*, by Judea Pearl, there is a chapter devoted to this phenomenon, called the "search-depth pathology," in which it is proved that if the error probability is constant, then the Shannon algorithm degrades to complete randomness as the depth of search depth goes to infinity. There are also some results that attempt to explain the empirical fact that the Shannon algorithm is nevertheless quite successful. But there is no rigorous discussion of how the Shannon algorithm might be modified to overcome the search-depth pathology.

What goes wrong with the Shannon algorithm? First, since it does not recognize that its guesses may be mistaken, it does not use the available information optimally. If, for instance, the guesses for the terminal nodes were 1,1,1,–1, from top to bottom, then it would seem obvious that A is a better choice than B, but in this case the Shannon algorithm treats A and B indifferently. Second, the Shannon algorithm does not attempt to determine which of the nodes should be most profitably examined, but instead always examines the deepest nodes it can reach. Deeper search means looking at more nodes, but if one then restricts one's attention to only the deepest nodes in the tree, searching deeper is no longer synonymous with using more information.

A Little Mathematics

We wish to resolve our puzzle about foresight and calculation by mathematical proof, and so without being overly technical, we describe here the theoretical framework in which we are carrying out our investigations. We begin with an arbitrary tree of nodes, at each of which we assign a player to move. The Zermelo values of the nodes are unknown to the players, but they can guess the value at a node (and perhaps other things) by observing it. In this context we can give mathematical formulas for the optimal choice of move, given any set of observations, and also the formula prescribing the best node to examine first. Recall that this constitutes the first step in our methodology. Afterward, we will describe the progress we have made with the second step, which is to extract general principles from the mathematics. Of crucial importance to the second step is that in the first step, we consider only those models in which spurious statistical correlations do not prevent sensible decision making. For example, in general some apparently irrelevant node might be perfectly correlated with the decision a player should make. We will not attempt to create a theory to handle such situations. By assuming the "Markov property," as explained below, we rule out such anomalies. As we will see, the Markov property is a reasonable description of many decision-making contexts.

To make our analysis mathematical, we must first come up with a rule for assigning values to the terminal nodes of the tree. For example, one often-used method is to assign values to terminal nodes randomly and independently. This approach has the feature that trees are "grown" backwards, namely from the terminal nodes to the roots, leading to results that are quite unnatural. We grow the trees from the root upward, using the Markov property.

To do this in a realistic manner, we suppose that positions come in several types. The type of a position tells us its true value along with several other things, which might include information about how difficult the true value is to guess and what types of positions it is likely to lead to. This is in accordance with the way good chess players tend to think about positions. They might, for example, look at a position and say something like: "this position is difficult to evaluate, but it seems clear that White's chances lie in a Kingside attack, while Black must seek counterplay in the center," or "this type of position tends to lead to very dull play in which neither side can gain an advantage."

We typically make the following assumption: once we know the type of a position x, our beliefs about the types of the successors of x are not affected by any knowledge about the types of any nodes that are not successors of x. This kind of assumption is often called the "Markov property." It is a reasonable approximation to what happens in games like chess, where once you observe all you can about a position, your predictions about the successors of that position should not be affected by knowledge or lack of knowledge about the types of positions you reached along the way, or by the types of positions you could have reached if you or your opponent had made a different earlier move.

Since even experts sometimes read a situation incorrectly, we want to include in our model some way in which errors occur, that is, to "quantify our ignorance." We assume that for any given set of position types, the probability that we will guess that the immediate successors of some position x have those types depends on two things: the actual types of the immediate successors of x, and the guess that we made for x itself (if such a guess was made). This assumption is similar to the Markovian assumption made earlier. It includes as an interesting special case the possibility that all guesses are made independently of one another, as in the example illustrated in the Figure 1.

(continued next page)

Some General Principles

We will give here five principles that can be deduced from our mathematical formulas. Afterwards, we will talk about how the Shannon algorithm fares with respect to these principles, and we will mention several guidelines used by human decision makers that seem to be in agreement with our principles.

1. *The proximity principle.* Think about the immediate consequences of your actions first! More precisely, if y and y' are both successors of x, and if y' is also a successor of y, then y is more informative about x than is y'. The relationship can sometimes be reversed if we are sufficiently certain of our guesses about y' and/or sufficiently uncertain of our guesses about y. In such a case, the "clear sight principle" comes into play, as explained below.
2. *The relevance principle.* Examine the most promising alternatives first! Or, in the context of games, continue your investigations first along the apparent intended lines of play. In particular, if you want to learn about x by looking at one of the immediate successors of x, look at the node y that is *a priori* most likely to be chosen by the player moving at x.

   If y and y' both succeed x, and y' is deeper in the tree than y, but *does not* succeed y, it might seem that we should first examine y. But this will not be true if along the path from x to y, the moves along the path to y' are more or less "forced" (i.e., the alternatives at each node on the path are obviously bad for the player moving at that node,) and if y' seems like it might be a good position for the player who is currently trying to make the decision.
3. *The family principle.* Make decisions that lead to many good options, rather than relying on one excellent possibility. Having many successors nodes with reasonably good prospects is better than having a few successors with great prospects. Formulating this principle in precise mathematical terms leads to some interesting questions of statistics that, to our knowledge, have never been addressed. Namely, suppose you observe two sets (or "families") of numbers, and want to choose the set that contains the largest number (the "best child"). If your observations are subject to error, how should you choose? The family principle says that you need to consider the apparent combined strengths of all the children in a family, rather than just that of the apparently best child. There are two distinct reasons for this. The first is that for the family that has a greater number of "promising" children, it is more likely that one of them will actually be much better than your observations led you to believe. The second is that for a family with one very promising child and many mediocre children, the fact that you observed many mediocre children makes it more likely that your estimation of the apparently outstanding child is too high.
4. *The stability principle.* Consistency increases confidence. If our guesses were accurate, we would guess values along the intended path that changed very little. Thus, if there is a terminal node whose predecessor nodes look consistently good from beginning to end, we should prefer that over a terminal node whose predecessor nodes appear to fluctuate in value, which in turn is preferable to a terminal node with consistently bad predecessors. If there is a lot of fluctuation in the values along the path to a terminal node in our search, we may want to increase our confidence in its evaluation by searching deeper.
5. *The clear sight principle.* If possible, base your decisions on clear-cut results. Our formulas show that observations with the lowest error probability typically receive the most weight. In the extreme case, when all of the error probabilities are very small, the Shannon algorithm might work well. We must emphasize the "very small" here, because this principle is essentially in conflict with the previous principles, and it doesn't take much in the way of observation errors to make them dominate. Judea Pearl shows in his book, under certain special assumptions on the decision tree, the most important of which is independence of the values of the terminal nodes, that if the proportion of absolutely clear positions in the tree goes to 1 as the tree gets deeper, then the search-depth pathology goes away, and basing your decision on the values of the terminal nodes is a good idea. This principle is the reason he gives for the successes of the Shannon algorithm. The Shannon algorithm should be modified to include some assessment of the size of the error probability for each node that it looks at.

Not surprisingly, there are several folk maxims that sound like the principles just given. For example, the proximity and stability principles both are related to the phrase "the end never justifies the means," while the family principle sounds like "don't put all your eggs in one basket." This last phrase is also a warning about reliance on the clear sight principle in cases where we think our guessing errors are too unlikely to worry about ("I've got a sure thing in the fifth race..."). "Follow your nose" could be interpreted as the proximity principle, and "go with a winner" is clearly a form of the relevance principle. "A bird in the hand is worth two in the bush" is a version of the clear sight principle. The mathematics confirms, but also gives precision, to the proverbs of everyday experience.

Good chess players also seem to be aware of the principles we have given. Grandmasters typically do not choose a move based on looking far ahead. Instead, they usually choose one or two plausible moves based on looking only one move ahead (the proximity principle), and then investigate those moves further by following what look like the most likely continuations (the relevance principle). In certain circumstances, they do look ahead to try to find positions whose value is obvious (the clear sight principle), so that they can avoid making blunders or falling into traps, or so that they can possibly find forcing moves that lead to a clearly won position. They have a keen sense of what types of positions will make available many good continuations for them (the family principle), and they are suspicious of lines that seem to end well, but are reached by way of positions that appear unsafe (the stability principle).

Evidence from the Chess World

Since the Shannon algorithm is unaware of its own "bounded rationality," it ignores the principles just enunciated. As far as we know, in the 40 years since Shannon first introduced his method, there have been only three modifications that attempt to compensate for these limitations. All three of them have dramatically improved the play of computer chess. The first one, introduced early on, allows the positional evaluator to assign a whole range of values to positions, even though there are only three possible true values for any position (win, lose, or draw). The effect of this procedure is that positions which are clear wins or losses are given extra weight (because they are given very high or low values respectively) in the Shannon algorithm. This is in keeping with the clear sight principle.

The second innovation is a limited kind of stability analysis. It is typically used in chess when a piece capture, say, White queen takes Black knight, occurs at the end of a path in the tree of moves being searched. Immediately after this capture, the value of the position appears to suddenly have changed, in favor of White, since Black is missing a knight. But it is often the case that in such circumstances, White's queen can be taken by Black on the very next play. Since queens are usually worth more than knights, the position is, in fact, good for Black. This phenomenon is known as the "horizon effect," and is avoided by searching deeper in those positions where pieces (such as the White queen) are "hanging," or vulnerable to being captured. Note how this is a special case of applying the stability principle.

The third modification is known as "singular extension," and was first introduced by the Deep Thought team in 1987. It noticeably improved the play of Deep Thought, and is now used by all of the top chess-playing programs. Briefly, the idea behind singular extension is that whenever the program finds a move that is vastly better than all of its alternatives, it looks deeper to check itself. Singular extension can be understood directly from the relevance principle. If a move to y following x is dramatically superior to its alternatives, then the relevance of successors of y will consequently also be high, and thus worthy of further investigation.

All of the modifications described here were motivated more by ad hoc practical considerations than by any deep understanding of general principles. There has been no attempt at all to be systematic, yet the three most important improvements in the Shannon algorithm can all be understood on the basis of our general principles. We hope that our work will lead to further improvements.

Where Do We Go From Here?

We have derived a set of general principles for optimal decision-making in complex environments. As a concrete application we investigated the game of chess, and we have tried to show that our principles explain all of the major improvements in computer chess programs (aside from those connected with computing speed). We further suggest that they roughly correspond to principles used by good human players.

We also believe that the practical application of our principles to chess play has not yet been exhausted. The clear sight principle and the relevance principle have indeed been partly embodied in the strongest programs. But the stability principle is used only in a very attenuated form, as a reason for further search-depth when the material is unstable. The application could be enormously enhanced by looking ahead after any position whose positional evaluation is unstable along the path leading up to it. The principle could be applied even without further search depth, by using the guessed values of the predecessors of a position to alter our guessed value for the position itself. The proximity principle guarantees that unless the positions are getting easier to evaluate, early evaluations are more reliable anyway. The family principle suggests that we should let our evaluation of a position depend somewhat on the guesses we make for its neighbors. The precise mathematical form of this will depend on the kind of ignorance that is present. Furthermore, implementation of a procedure based on the family principle is probably less compatible with the Shannon algorithm than any of the other suggestions we have made. But we believe that after much research, there may be something of practical value here as well.

As far as the world outside of chess goes, it seems that people have been at least vaguely aware of our principles all along. But by giving them a somewhat more precise formulation, we have illustrated how mathematics can refine and clarify, and even improve, the way in which we make day-to-day decisions.

—John Geanakoplos and Larry Gray
June 27, 1991

John Geanakoplos, Yale University, was 1990–91 co-director of the SFI Economics Research Program, and Larry Gray, a professor at the University of Minnesota, was a participant in the program.

Education

An Undergrad's View

For the undergraduate, an internship at SFI offers a challenging and provocative experience. Alan Kaufman, a recent Yale graduate, was at the Institute from February through July, 1991, as the first Robert Maxwell Undergraduate Intern. Here he describes the perils and rewards of his research visit. Kaufman concentrated on two projects working with External Professor Stuart A. Kauffman: one focused on strategies to optimize NK landscape functions. These schemes were motivated by economics, and attempted to model such issues as firm formation and size, selfish vs. selfless agents, etc. The other project used a random grammar approach to illuminate nonequilibrium economies. The intent of that model is to explore areas such as bounded rationality, time inconsistencies in roll-ahead planning, and technological innovation, evolution and growth. A "New Englander by birth and outlook," Kaufman has returned to the East Coast where in September he begins graduate study in Operations Research at MIT.

This summer, Kaufman was joined by two additional interns. Erik Schultes, a biology/geology major at Humboldt State University in California, attended the Complex Systems Summer School before joining the research staff for the months of July and August. He continued work on Kaufman's random grammar project.

Alexander Gray, a senior in Computer Science at the University of California at Berkeley, worked with SFI External Associate Professor Alan Lapedes and his research group on the analysis of protein structure using information theory. Gray's research focused on a mutual information tool which is used to characterize correlations between codons; further, he applied this analysis to a large body of NIH data.

Ginger Richardson asked me to write something up for the SFI Bulletin. "Make it personal," she said. "What it's been like for you being here...the human stuff." Her request pushed me to reflect upon my stint at SFI. I certainly feel at home here now, and the people are terribly nice, and the stream of interesting visitors seems unending. But that's getting ahead of myself.

The story starts last December. I had just finished my undergraduate degree, and my applications to graduate schools and the Peace Corps were done and mailed. My short-term plans were as fuzzy: I had a job offer to caretake a remote winter climbing hut on the shoulder of Mount Adams in New Hampshire; some friends from school were heading down to the jungles of Brazil and had asked me to come along; and all the while my parents were urging me to "do something real."

At this point I heard about the Santa Fe Institute from a friend, Marc Lipsitch, who had attended the 1990 Summer School and enjoyed his experience. I was interested, so he gave me Mike Simmons' name and I fired off a precocious letter. I am highly grateful that Mike didn't file that impetuous and unsolicited request in the recycling bin. Instead, he passed it on to Stuart Kauffman, and the next thing I knew I was on the way to Philadelphia to meet the eminent biologist with a name curiously similar to my own.

The day I spent in Stu's lab was a whirlwind of ideas and names. I couldn't follow much of it, but it sure sounded neat. Metaphor followed metaphor in a rapid tumble: networks of light bulbs playing games by bumping belly buttons, artificial soups of recursive functions evolving like early life, the frozen red islands and the twinkling green seas of NK fitness landscapes, the edge of chaos being some sort of evolutionary attractor, the phase transitions of random button and thread graphs...somehow, the wilds of the Amazon seemed tame in contrast. Stu offered me an internship at SFI, and unhesitatingly I accepted.

Stu sent me first to work with one of his colleagues, Paul Romer, an economist at the National Bureau of Economic Research in Palo Alto. Paul is exceptionally friendly and patient; together we played with some simple economic applications of genetic algorithms and Stu's NK model. My brief stint at NBER was a fine experience, and served to prepare me, as much as possible, for my arrival at SFI.

I arrived in Santa Fe in early February and was overwhelmed.

My first impressions of the Institute were the stacks and stacks of cardboard boxes lining the halls, and the impressive library of math and science volumes out front. Together, these gave me the impression of an organization less concerned with appearances than with "doing science." That first week, as I began to meet other folks working at SFI, their enthusiasm and intensity towards their research confirmed the impression.

As I said, I was overwhelmed. Interesting things seemed to be happening on all sides, and I thought I didn't have enough math background to understand *anything*. (It was certain I lacked the physics and economics.) Having had some computer experience, I set about making myself useful by coding up some simulations of a new economic model Stu and Paul had dreamed up. Even that proved difficult at first, for my background was with VAX mainframes. With generous amounts of help from Robin Justice, the manager of SFI's computer facilities, and SFI researcher Michael Angerman I learned some UNIX without doing major damage to the network or myself.

Stu pulled Mats Nordahl, a SFI postdoc, into the group working on the economic model. As Stu splits his time between his lab at UPenn and the Institute, and is pretty busy even when in Santa Fe, I turned to Mats with my barrage of daily questions. His advice was always helpful—though it would sometimes take me weeks to realize it. Many of my ideas were crazy or simply wrong. Mats endured them all with good humor, and helped keep me on track.

The Institute is dedicated, paraphrasing its mission statement, to scientific research and education. Some of its activities fall distinctly into one of these two areas. The Complex Systems Summer School and the Public Lecture Series, for example, are clearly educational endeavors, whereas the Institute's series of conferences and symposia are research directed. The undergraduate intern program, however, spans both categories. This dual emphasis can lead to some tension. On the one hand, I felt my purpose was to absorb as much as possible in a variety of fields. On the other, I felt an obligation to "get something done," to accomplish some interesting and novel bit of research. At times, these goals felt contradictory. Lacking chunks of relevant background, I felt hampered in my research attempts. Without a sense of discovering something noteworthy, I doubted the legitimacy of my presence in a community of actively researching scientists.

After two months at the Institute, I began to feel more at home. I was reading voraciously, recklessly attempting every volume in the SFI/Addison-Wesley Studies in the Sciences of Complexity series. Probably I assimilated only five percent of the material, but I gained an overview of what the phrase "complex systems" can encompass. I began to see the connections that link the different strains of research that happen at SFI. Adopting a large-scale outlook, realizing the breadth of the Institute's interests, getting some interesting preliminary results from some experiments—and my confidence increased. I worried less about what my role ought to be and simply relished the daily excitement of working at SFI, trying to allow neither my directed research work nor my random educational explorations to gain an upper hand over the other.

Alan Kaufman, SFI undergraduate intern. Photo by Cary Herz © 1991.

From my personal experience (a statistically significant sample of one!), the undergraduate intern program is a great idea and a great success. My internship at SFI has afforded me the experience of full-time research, something I'm unlikely to encounter again until two years into my graduate program. I've also had the luxury to explore a wide range of disciplines. The interdisciplinary nature of the Institute has been the largest boon, introducing me to novel ideas and thinkers in fields—physics, economics—previously unfamiliar to me.

So now, after five months in Santa Fe, I'm trying to wrap up some loose ends, so as to leave behind a cohesive contribution when I leave in a month. There's much remaining to do—a few more critical simulations to try, some interesting Summer School lectures to drop in on, and the last round of spring alpine wild flowers demanding appreciation. Time's moving at a rapid pace. Probably I won't be able to squeeze in all my plans, but that's OK.

I am very grateful to have had the opportunity to spend a large chunk of time at the Santa Fe Institute. It's been an amazing experience. I don't regret turning down the Amazon for the light bulbs. The only problem remains my folks—I call home babbling about nonequilibrium and strange attractors, and *they* still ask if it's *real*.

—Alan Kaufman

Summer and Science in Santa Fe

Daniel Stein, co-director of the 1991 Complex Systems Summer School. Photo by Cary Herz © 1991.

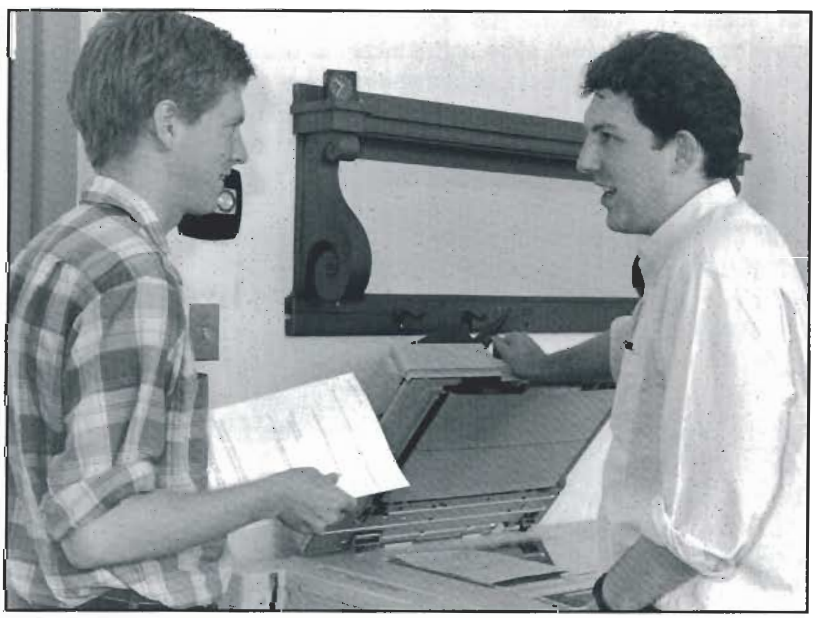
American universities may not be ready for interdisciplinary research, but their students are.

Representatives of the 60 graduate and postdoctoral students who attended the Santa Fe Institute's 1991 Complex Systems Summer School said the environment was mind stretching, inspirational, creative, and surprisingly non-competitive. Applicants heard about the summer school through their professors, classmates or SFI literature. For most, the chance to do interdisciplinary research in complex systems while living in Santa Fe proved irresistible.

Held at St. John's College for the fourth consecutive year, the 1991 program was co-sponsored by the Center for Nonlinear Studies at Los Alamos National Laboratory; the Los Alamos Graduate Center at UNM; Sandia National Laboratories; SFI; Harvard University; Stanford University; Arizona State University; and the universities of Arizona, California, Illinois and New Mexico. Principal financial support was provided by the National Institutes of Health, National Science Foundation, Office of Naval Research, and the U.S. Department of Energy.

The students represented a gamut of scientific disciplines—from mathematics to genetics to nuclear physics—and ranged in age from 22 to 44. Chosen from among 100 applicants, they came to Santa Fe from colleges and universities around the country. The variety of backgrounds, academically and otherwise, made for some stimulating conversations.

"Some loud conversations," Shane Hubler, a graduate student in mathematics from the University of Wisconsin-Madison, said with a laugh.



Peter Hraber, 1991 Summer School Assistant, and P. R. Andrews, Cambridge University. Photo by Cary Herz © 1991.

"I don't think you could find a course like this anywhere else," said graduate student Jutta Escher from the physics and astronomy department at Louisiana State University. "It was amazing to see how well people communicated," she said. "It's exciting to see a field when it's just starting off."

A minimum of crossdisciplinary communication exists at their home institutions, several students said. The summer school exposed them to new ideas and research tools, sparking interest in disciplines other than their own while, in most cases, reaffirming their original career choices.

Sharon Reilly, a postdoctoral student from the genetics department at the University of Michigan, said there is often pressure to conform in graduate school.

"Here the constraints on my thinking were lifted," she said. "You see everyone else doing wild things and think, why not?"

Neural nets, spin glasses, genetic algorithms, and cellular automata were among the "wild things" students encountered in lectures and research projects.

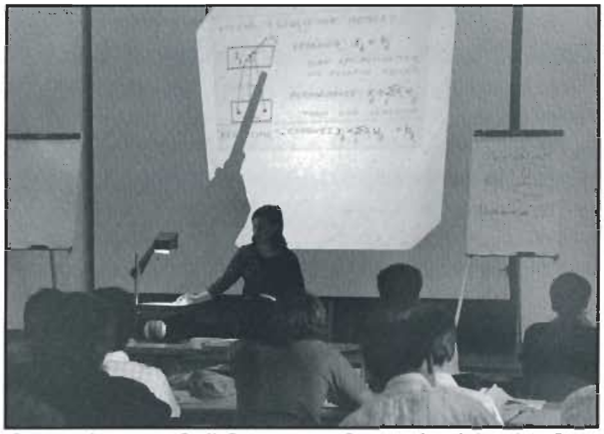
Students attended two lectures by visiting professors each weekday morning. Afternoons included at least one lecture given by SFI External Faculty members or Los Alamos National Laboratory staff members. Lecture topics ranged from "Noise, Fractals and Scaling" by Michael Shlesinger, Office of Naval Research, to "Artificial Life" by Christopher Langton, Los Alamos National Laboratory, to the "Statistical Mechanics of Neural Networks" by Sara Solla, AT&T Bell Laboratories.

Besides hearing lectures, students broke into small groups to work on special research problems. This year as in the past, some of these groups have presented their research results as lectures during the last week of summer school and have contributed papers to the annual volume of summer school lecture notes. 1991 research projects ranged from the modeling of physiological neural nets and neural network diagnosis of medical images, to optimization and equilibrium in economics.

Susan Minkoff, a graduate student from the mathematical sciences department at Rice University, said attending the Complex Systems Summer School has prompted her to re-evaluate her research methods and herself.

"My department is classical and somewhat conservative" she said. "At home, I'm the department radical. Here I found myself arguing the conservative point of view."

Hubler described himself as "somewhat of a generalist," having traveled through all branches of mathematics. "I've had a lot of doubts in graduate school," he admitted. "The summer school has reaffirmed my belief that math is something that I should continue with." He plans to forego a university tenure track in favor of consulting. "I've rediscovered a part of myself—I still have creativity and an ability to come up with solutions."



Course lecturer Gail Carpenter, Center for Adaptive Systems, Boston University. Photo by Cary Herz © 1991.

The size and length of the summer school suited most of the students. "It might be hard to sustain the spirit longer than four weeks," Escher said. Hubler added that the number of students allowed for plenty of different viewpoints but it was still possible for everyone to know everyone else.

The lecturers were surprisingly entertaining and approachable, according to Armando Manduca, Mayo Foundation, "I thought they'd be terribly serious, but they were playful," he said, adding that the lectures were never repetitive. "If someone gave five lectures, each lecture was completely different."

The lecturers routinely ate lunch with their students, Reilly said. The atmosphere of the summer school in and out of the classroom was refreshingly varied and noncompetitive, more than one student noted.

"The students didn't feel they had to do science all the time to be successful scientists," Reilly said. She described her classmates as "multi-dimensional," having a lot of knowledge and talent in areas other than their specific disciplines.

In their free time, students played musical instruments, hiked in the mountains or visited Santa Fe's museums and art galleries. There conversations among the students also proved to be multidimensional.

In Germany there is a lot of discussion about scientists taking responsibility for their research, Escher said. On American campuses, there isn't as much conversation on this topic, she said. The SFI Summer School proved to be an exception. Discussions about artificial life raised many ethical and moral questions.

"If you discover knowledge, you are responsible for it, not the politicians," Escher said.

Although the school lasted only one month, several students said they expect the experience to benefit them throughout their careers. They plan to incorporate cross-

(continued next page)

Course Lecturers

Gail Carpenter
Center for Adaptive Systems, Boston University

Predrag Cvitanovic
NORDITA

John Denker
AT&T Bell Laboratories

Bernardo Huberman
Xerox Palo Alto Research Center

Christopher Langton
Los Alamos National Laboratory

George Mpitsos
Mark O. Hatfield Marine Science Center

Fred Nijhout
Zoology, Duke University

James Sethna
Physics, Cornell University

Carla Shatz
Neurobiology, Stanford University

Michael Shlesinger
Office of Naval Research

Sara Solla
AT&T Bell Laboratories, Holmdel

Nicholas Strausfeld
Arizona Research Laboratory Division of Neurobiology, University of Arizona

David Tank
AT&T Bell Laboratories, Murray Hill

Computer Laboratory Vendors

The Institute is grateful to the following companies for lending computer and communications equipment and software to the Summer School:

Sun SPARCstations, Debbie Maestas, Sun Microsystems, Inc., Albuquerque, NM

Macintosh IIs and laser printer, Glen Banks, Apple Computer, Phoeniz, AZ

Island Write, Draw, and Paint software, Nancy Carter, Island Graphics Corporation, San Rafael, CA

Telebit modems and Netblazer, Lou Elmore, Telebit Corporation, Sunnyvale, CA

Apple Laserwriter, Jill Epstein, Computerland of Santa Fe, Santa Fe, NM

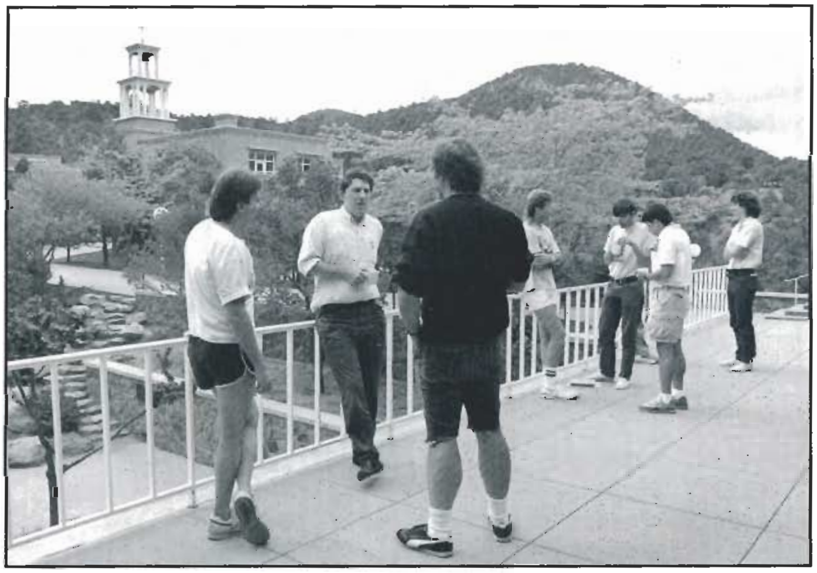
Summer & Science (cont'd.)

disciplinary research into future projects and believe that their thinking has been expanded from conversations and research projects with scientists from other disciplines.

Attending the summer school has given Reilly the ability to talk to computer scientists, physicists and others about problems in genetics, she said.

"I feel more valuable as a scientist," she said. "I think I can play a larger role in science."

Asked for suggestions on improving the summer school, several students commented that there were not enough computers for 60 students, there were too many lectures during the last week when students were finishing up research projects, the SFI library was spare, and having only one lecture site was a bit monotonous.



Students on the St. John's campus for the 1991 Complex Systems Summer School. Photo by Cary Herz © 1991.

However, they noted that the program seemed well organized and functioned smoothly. "The organizers made it work with minimum visibility," Reilly said. "Andi Sutherland was very efficient in getting everyone squared away once they arrived in Santa Fe," Minkoff said.

Former students of the complex systems summer school have gone on to organize SFI workshops and conduct research with external faculty members. SFI Executive Vice President Mike Simmons hopes the trend continues.

"Research in the sciences of complexity is still a relatively new field," he noted. "Our summer school attracts the brightest scholars from a range of scientific disciplines."

"There needs to be a safe place to do interdisciplinary research," Reilly said. "I'll be drawn to the Santa Fe Institute as long as I'm interested in the science."

—Diane Banegas

Diane Banegas is a Public Information Specialist at Los Alamos National Laboratory.

Audification

Using Sound to Understand Complex Systems and Navigate Large Data Sets

Audification[1] refers to the use of changes in sound to "display" the status of a multi-dimensional system. I am developing this technique[2] to contribute to scientists' ability to comprehend complex dynamical systems and large data sets. Currently, 3-D graphics displays are most frequently used in the attempt to comprehend multiple dimensions. By use of color and time, such displays may represent four or as many as eight dimensions (variables) simultaneously.[3]

Higher-dimensional systems with 20 or 30 variables may have dynamic relationships between the variables that are too complex to understand via such limited visual displays. Audification may bring comprehensibility to such higher-dimensional dynamic systems. This technique enables the data analyst to employ the substantial pattern-recognition capabilities of the auditory channel.[4] When combined with visualization, audification can contribute significantly to the understanding of complex data.[5]

A simple example of a direct audification translation might include the use of amplitude (volume) to track one variable, frequency to track another, brightness a third, spatial location a forth, and so on. However, to represent higher dimensions, more complexity is required of the sound. This complexity can be obtained by creating parallel audio streams (polyphony) and by generating a single sound stream with many levels and types of parameter

(continued next page)

Lectures Volume

1990 Lectures in Complex Systems, edited by Lynn Nadel and Daniel L. Stein is now available through Addison-Wesley. This is the third lectures volume in the Santa Fe Institute Studies in the Sciences of Complexity Lecture Series; the series' cumulative effect is not only to record what has already been done in the field but also to contribute to defining complexity's future evolution. The book presents topics covered at the 1990 summer school's seminars and lectures; discussions include stochastic processes, fluid flow, pattern formation, information-based complexity, motor system problems, and the nature of adaptive change.

The volume is available in hardback; cost is $48.50. To order call Addison-Wesley Publishing Co. at 1-800-447-2226, or write to Addison-Wesley Publishing Co., Advanced Book Program, 350 Bridge Parkway, Suite 209, Redwood City, CA 94065.

variability. I am exploring the use of increasingly complex variables and manipulating variables on different time scales to achieve high-dimensional modeling tools.

Two or three melodic voices can be simultaneously recognized and defined (four voices in trained musicians or conductors). This falls far short of the dimensionality required of many models. My current work extends the tools of audification beyond clearly pitched sounds to include complex sound masses. Such sound masses may represent multiple dimensions within one audio stream. Polyphony is employed when additional dimensionality is sought or when multiple voices are helpful in representing distinct sub-groups of the data stream.

The applications of audification include understanding numerous aspects of the sciences of complexity, including complex computer models such as ecosystems, immune systems, and economic or disarmament scenarios. There are also applications to work in adaptive computation (artificial life), virtual reality (veridical systems), and the monitoring of complex laboratory, medical or industrial processes. This work could have uses in general education (for example, understanding mathematical concepts or historical trends) and systems for handicapped persons, where the use of sonic feedback has enabled blind chemistry students to employ complex laboratory tools that normally have only graphic output.[6]

Audification as a Technique to Encourage Mental Synthesis

Comprehending complex data sets has historically been approached analytically. As the analyst receives each package of data, he or she associates the data with the real parameter of what is being modeled and tries to perceive trends, predict behavior, and so on. Audification may be employed in this manner, but only when relatively few dimensions are being audified. When more dimensions than can be cognitively tracked are being represented by sound, the mind may be compelled to "let go" of this one-to-one, analytical approach and open up to the broader trends and relationships in the data under consideration. Thus, I believe, audification has the capacity to shift the observer's analytical perspective toward a more synthetic approach.

One might say that audification helps one understand the "Gestalt" of the data, thereby avoiding the pitfalls of the investigator who focuses too quickly on specific data and loses the overall meaning.

Mental Audifications: Audiation

Many of the inspirations as to how to manipulate the sound and some of the decisions as to what sound manipulation techniques to actually implement will be dependent upon the ability to "preview" the sounds or the parameter manipulations in one's mind. As we develop the audification tools, we are trying to predict what differences in sound will be perceivable, which will be genuinely useful, and how variations of different parameters will effect each other and the overall sound. The capacity to hear certain sounds within one's mind and to then mentally transform those sounds will be referred to, for purposes of this discussion, as *audiation*.[7]

Even more important than the capacity to hear and transform sounds in the mind will be the extent to which a scientist can "re-audiate" (mentally hear) sound transformations they have already experienced when running their models. This capacity, which I call *dynamic sound memory* (DSM), may be developed as the data analyst gains more experience with audification. DSM will support the data analyst's ability to reflectively consider the results of his/her work. Directly related to DSM is the ability to hear specific model states and by transforming the sound in their minds do "what if's" on those states.

Certain relationships and trends heard in the original audification will suggest extensions and developments in purely sonic terms. Then, by altering the real model variables to test data/sound correlations, the creative results of this audification can be evaluated.

Navigating Through Audified Data Fields

One of the problems presented by extremely large volumes of data is finding the areas of relevance to the researcher. This problem is intensified as more dimensions are added to the data set. Audification has the potential of allowing the researcher to use a physical interface to control a number of independent model variables and provide real-time sonic feedback on the system as the values of those variables are changed. When the sound indicates to the user that the model variables are displaying interesting characteristics, the researcher may then use other tools, graphic, text, or other audification techniques to further investigate these regions.

This process of actively searching large data sets, which I call *navigation*, might work like this:

A large data set (with, say, fifteen dimensions) is established. This may consist of equations representing data relationships or files of calculated data. A multi-dimensional input device, such as a Polhemus 6-Space tracker or a Moog/Kramer multi-dimensional keyboard interface, is interfaced with the computer system such that control information from each dimension of the input device moves a pointer through each variable's data set. A change in any dimension causes the system output to update and reflect the status of the model with the newly selected values. Where the model consists of equations rather than calculated data, the input device would manipulate model variables according to the model's rules, with the output data streams being calculated on-the-fly.

Now the system user may *navigate* through the data space, listening from anomalies, coherence, boundaries, or any interesting sonic results. One may find, for example, areas of the model where there is a sudden calming of the sound. These may represent strange attractors in a chaotic system. One may find certain regions where a usually stable sonic variable undergoes extreme changes. There may be certain trajectories that indicate interesting phenomena. These trajectories could be probed, or "played," to determine their boundaries. This process I will call a "what-if real-time" (WIRT) technique.

If one were to use the X, Y, and Z dimensions to represent real space in geographic model, then the three input controls of roll, pitch, and yaw could be mapped to other model variables. The roll variable might be utilized to represent time, while pitch and yaw represent two independent what-if variables. With such a system, one could navigate a large data space, listening to the audified representations. The meteorologist might represent the variables of temperature, atmospheric pressure, and wind speed auditorily. Or the geologist might navigate geological formations, pressures, and temperatures beneath the surface of the earth employing audification feedback. On a smaller scale, X, Y, and Z may represent one's position within a semiconductor, using pitch or yaw to manipulate the dimension of electrical charge. For a system in which gases are being combined, proportional gaseous mixtures could be similarly represented. Or, in the tissues of a living system, cell chemistries could be thus represented, providing either an overview of the system's status or, once again, a WIRT navigation of the system.

—Greg Kramer

Notes

[1]Author's term.

[2]Auditory data representation was first introduced by the chemist E. Yeung and later developed by S. Bly, S. Smith, S. Frysinger, et al. For an overview of the field see Frysinger in Farrell[3] below.

[3]E. J. Farrell, ed, *Extracting Meaning from Complex Data: Processing, Display, Interaction,* Proceedings of the SPIE, vol. 1259, Bellingham, WA, 1990.

[4]For an excellent consideration of auditory pattern recognition, see A. Bregman, *Auditory Scene Analysis: The Perceptual Organization of Sound,* MIT Press, Cambridge, MA.

[5]S. Bly, "Sound and Computer Information Presentation," unpublished dissertation, University of California, Davis, 1982.

[6]D. Lunney and R. Morrison, "Auditory Presentation of Experimental Data," in Farrell[3] above, pp. 140–146.

[7]In order to conveniently distinguish the concept from that of "audification."

New Features of SFI Education Effort

Audification

Apple Computer recently awarded SFI Member Gregory Kramer a grant to study how sound could improve the way students learn with computer simulations. Support from the Apple Classrooms of Tomorrow (ACOT) project includes Apple Macintosh computers and peripherals and funds initial software development. The award spotlights just one of several new educational initiatives at SFI.

Today's computer simulations often use graphs and icons to represent information but the use of sound to represent data is relatively untried. Kramer calls using sound to represent data "audification." It relies on the brain's natural ability to decipher a variety of tones, pitches, and sounds. Although quite new, audification holds promise of being able to provide a low resolution display of many independent variables simultaneously (see "Audification" on page 14).

Working with primary and secondary students in Arizona schools, an ACOT team has developed a computer model of the state's Kaibob Plateau: its variables include factors such as the deer and predator population of the area, available food, and hunting licenses granted. Students change initial conditions and repeatedly run the model to test ecological outcomes. The eco-model's icons are compelling, so much so that kids consistently approach the system as they would a video game, often basing their conclusions solely on the icons, even if the symbols do not accurately represent the data in question. The recent grant to Kramer focuses on adding audio data representation to the Arizona model. Audification, with its capacity to be as perceptually compelling as an animated icon, should help students monitor many more dimensions simultaneously as well as gain a better intuitive understanding of the data as it changes in time.

Kramer draws on many years' experience working with sound and electronic music techniques and on his background working with engineers to bring their ideas to fruition. He is currently concentrating on using sound as a means of comprehending complex data. "It was instantly clear that SFI was the ideal place to work on audification," he says. "I needed access to scientists with complex models and data sets, and the Institute is one of the few centers devoted to the sciences of complexity. It is my hope that my work will lead to new tools that help scientists extract meaning from their data."

Winter School

Arizona is the site for another educational initiative involving SFI, the 1992 Complex Systems Winter School. Co-sponsored by the Institute, the Physics Department and the Center for Complex Systems Studies at the University of Arizona, and the Center for Nonlinear Studies at Los Alamos National Laboratory, this intensive two-week school is an outgrowth of the highly successful Complex Systems Summer School annually held in Santa Fe.

The focus of the Winter School, to be held in Tucson, Arizona, January 12–24, 1992, is the geometrical and dynamical behavior of scaling complex systems. "A principal research theme of the past decade has been the self-similar and hierarchical structure of dynamical systems of all kinds." says Peter Carruthers, head of the Physics Department at the University of Arizona and Director of the school. "This school will bring together outstanding lecturers to review the progress and interdisciplinary character of related fields." The School will give a limited number of highly qualified students at the advanced graduate and postdoctoral level a concentrated introduction to these closely related and ubiquitous phenomena, leading to a current research-level knowledge of the subjects. Although speakers are still being added to the roster, topics include turbulence, percolation, self-organized criticality, 1/f noise, mathematics of hierarchical systems (emphasizing fractals), fractal graphics, and scaling structures in physiology, galaxies, and elsewhere in nature.

Campus Collaborations

Clare Congdon, David Laser, Sharon Reilly, and Erhard Bruderer—four alumni of this year's Complex Systems Summer School—represent another new educational impulse at the Institute, that is, active collaboration between SFI and various university communities to foster continuing educational interaction on an institutional basis. The four young scientists came to the Summer School following an introductory graduate complex systems course taught at the University of Michigan by SFI External Faculty member John Holland. Holland's course is part of a joint SFI/U. Michigan program which in part explores the prospects for ongoing research and educational exchanges between the Institute and university communities. It's anticipated that as ongoing joint institutional collaborations develop, more university students will move increasingly between research stints at their home institutions and SFI. "For the past several years students who have completed course work for their doctoral degree have, with the agreement of their home institution, conducted thesis research and writing in residence at SFI under the direction of a member of the SFI External Faculty," says Executive Vice President Mike Simmons. "With the growth of SFI/campus collaborations, I see an increasing number of students, studying here not only with SFI External Faculty but also working here as part of off-campus research groups from their home institutions. We welcome this as an aspect of the

Until recently the field of complex systems, at least as now interpreted by the researchers associated with the Santa Fe Institute, did not exist as a recognized research area. This is rapidly changing as an increasing number of scientists are beginning to work on complex interdisciplinary problems using newly emerging techniques. Nevertheless, these researchers, who employ ideas and techniques from a variety of fields to attack complex problems, may find that there is no single professional journal in which their work obviously belongs. For several years scientists at the Santa Fe Institute have been discussing the idea of creating a special journal in which the highly interdisciplinary work on complex systems would find a natural home. Simultaneously, the publishers of scientific journals were approaching both the Institute and individual scientists to discuss the need for a journal that would give broad coverage to the sciences of complexity.

Another Journal?

Some argued that the world is not in need of new journals. On the contrary, the libraries of academic institutions worldwide are overburdened by the ever increasing costs of an ever increasing number of specialized journals. It was argued, quite cogently, that the proper place for the publication of scientific research employing a complex systems approach to, say, economics is in the established journals that are read by economists.

Nevertheless, new specialties associated with complex systems are emerging: areas such as nonlinear dynamics, genetic algorithms, neural computation, and artificial life. In each of these fields, and others, new journals are springing up to meet the need for an arena in which specialists can publish their results for an audience of informed peers. Even as complexity is emerging as a new field of research, it is in danger of fragmenting into a number of disjoint subfields that will not communicate adequately with each other because each will be served by its own specialized journals. The result might be that the common threads and integrative aspects of the emerging sciences of complexity would be lost.

The Santa Fe Institute began serious discussions of these issues out of a belief that a properly conceived journal encompassing the integrative aspects of the sciences of complexity offers the hope of preventing this fragmentation and furthering the development of the study of complex systems by fostering desirable cross-disciplinary communication. More than a year ago the President of the Institute, George Cowan, appointed an *ad hoc* committee to consider whether and how a new journal might serve the emerging sciences of complexity.

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The committee, chaired by Science Board Co-Chair David Pines, included Michele Boldrin, Ronda Butler-Villa, David Campbell, Doyne Farmer, Stuart Kauffman, Alan Perelson, and L. M. Simmons. The committee's report, strongly recommending that the Institute proceed with a journal, was endorsed by the Science Board and the Board of Trustees. With the advice of the committee, the Institute president entered into negotiations with potential publishers and began the search for an Editor in Chief and boards of associate editors and advisors.

The result was the recent announcement, jointly by the Santa Fe Institute and Pergamon Press, of the founding of a new journal, tentatively entitled *Complexity, An International Journal of Complex and Adaptive Systems.* Said Dr. Peter Shepherd, Editorial Director of Pergamon, "I believe we have identified a publication for which there is a truly important niche, and which will encourage in an essential way the development of the sciences of complexity."

Shepherd also said, "We all agree that one factor which will be critical to the success of the new journal is the Editor in Chief." In March, it was announced that Prof. Harold Morowitz, a distinguished biophysicist, member of the SFI Science Board, and Clarence Robinson Professor at George Mason University, had accepted the post of Editor in Chief of *Complexity*. SFI President Emeritus George Cowan said, "As a highly respected scientist with very broad interests, Harold Morowitz is an ideal choice for Editor in Chief."

Goals

Among the goals of the new journal is to provide a timely and widespread means of communication for scientists working in different subfields of the sciences of complexity. It is also intended to provide understandable reports of recent research results that may prove of general applicability and to encourage the examination of the extent to which novel computational techniques, theoretical concepts, and models developed in one area of the sciences of complexity may be applicable to other areas. Said committee chair David Pines, "This journal will provide a vehicle for a continuing critical examination of the extent to which there exist underlying concepts of general applicability in the sciences of complexity."

The journal will consist principally of refereed scholarly papers in the sciences of complexity. The field will be broadly covered with an emphasis on papers that suggest or apply possible integrating concepts or themes of considerable commonality. Scholarly, commissioned review articles will be a regular feature. A part of each issue will be devoted to concise, lively, and up-to-date commentaries, book reviews, and news items. The journal will aim to serve an international community of physical, biological, mathematical, behavioral, computer, and social scientists carrying out research on complex systems. Said SFI President Edward Knapp, "This will not be a journal simply of the Santa Fe Institute. We intend *Complexity* to be an international journal of great breadth."

Initially *Complexity* will be published in four issues per year, a number that will increase as the demand increases. The first issue is planned for early 1992. The editorial offices of *Complexity* will be in the Publications Department of the Santa Fe Institute, under the direction of an Executive Editor. The Institute and Pergamon are currently in the process of selecting the Executive Editor. The Editor in Chief and the Executive Editor will work closely with a board of Associate Editors who will participate in the process of soliciting and selecting articles for the journal and will assist in choosing appropriate referees. A distinguished international advisory board will advise Morowitz and the Associate Editors on the operation of the journal.

The publication office will be at the Pergamon Press in Oxford, England. SFI Director of Publications Ronda Butler-Villa said, "Working with an overseas publisher provides an exciting opportunity to move toward complete electronic publishing, first to ease costs and delays of the printing process by providing electronic camera-ready copy, maybe even electronic color separations, and hopefully later as a means for journal distribution."

—L. M. Simmons, Jr.

Associate Editors of *Complexity* Chosen

Editor in Chief Harold Morowitz recently announced the selection of a Board of Associate Editors including:

Prof. Michele Boldrin, Economics Department, Northwestern University

Prof. Peter Carruthers, Physics Department, University of Arizona

Prof. Marcus Feldman, Director, Institute for Population & Resource Study, Stanford University

Dr. Wojciech Zurek, Theoretical Division, Los Alamos National Laboratory

Morowitz Named Editor in Chief

Editor in Chief of *Complexity* is Harold Morowitz, Clarence Robinson Professor of Biology and Natural Philosophy at George Mason University. Morowitz brings a formidable combination of scientific achievement and editorial expertise to this new post. Prior to his appointment as Clarence Robinson Professor, he was Professor of Molecular Biophysics and Biochemistry at Yale University. Author of twelve books, Morowitz's latest volume, *The Thermodynamics of Pizza*, is forthcoming from Rutgers University Press. His other titles include *Ego Niches, An Ecological View of Organizational Behavior* (Ox Bow Press); *The Wine of Life and Other Essays on Societies, Energy and Living Things* (St. Martin's); *Mayonnaise and the Origin of Life, Thoughts of Minds and Molecules* (Scribners); and *Cosmic Joy and Local Pain, Musings of a Mystical Scientist* (Scribners). Morowitz is a contributor to *Psychology Today*, *The New York Times*, *Discover*, and *The Sciences*.

Currently a member of National Advisory Research Resources Council of the National Institutes of Health and the Board of Biology of the National Research Council, he has in the past consulted for NASA and for the National Research Council's Committee on Use of Laboratory Animals and Biomedical and Behavioral Research, and served as an Expert Witness at the Creation-Evolution Trial at Little Rock, Arkansas in 1981. He is a member of The Biophysical Society, the American Institute of Biological Sciences, and the Explorers Club.

Morowitz' association with the Institute began in 1987, when he headed a five-week SFI summer workshop on the Matrix of Biological Knowledge. Out of that meeting has grown the Biomatrix Society, a group addressing the pressing need to organize, intelligently access, and make available widely the wealth of biomedical information confronting researchers. To date that project has garnered nearly one hundred active members.

This meditation on computers, classics, and contemporary thought was written by Morowitz during the Matrix summer workshop which took place on the St. John's College campus in Santa Fe. His observations reflect the breadth of vision he brings to his new task.

Harold Morowitz, George Mason University. Photo by Cary Herz © 1991.

Past, Present, Future

It is a quiet Saturday afternoon, and I sit in the library of St. John's College in Santa Fe, New Mexico. This institution has a curriculum based upon the "Great Books," those hundred or so classics that are judged to have been most influential in molding contemporary thought. The educational format lays heavy stress on the dialogue across the generations, the importance of making education an integrative experience over the range of human civilization.

My reason for being at this place at this time is to participate in a workshop on computer data bases in biology and the use of computers, data management techniques, and artificial intelligence approaches in developing theories for biology and medicine. For the next few weeks, two large on-campus laboratories provide facilities for small computers, larger work stations, and telephone hookups to major data banks throughout the country. I am conscious of being at a way station between a past that reaches back to the oral tradition of Homer and a future in which machine-assisted thought will be generating truly novel approaches to human understanding.

As I query data bases in distant cities, two distinct thoughts come to mind. One is the idea of Marshall McLuhan that, "Today, after more than a century of electric technology, we have extended our central nervous system itself in a global embrace, abolishing space and time as far as our planet is concerned." The other is the notion of Teilhard de Chardin that the evolution of reflective thought has produced the noosphere, a network of interacting thought that encircles the globe and promises to change the planet as profoundly as the advent of the biosphere billions of years ago.

I am trying to find a thread that winds its way from Thucydides to Turing, from Vergil to von Neumann, from Machiavelli to Minsky. The task is a difficult one. It is always possible to look back and assess a historical development, but living in the middle of a great change, how does one evaluate it?

As the mind begins to drift, I wonder who among the greats of the past would be comfortable amidst us as we stroke our keyboards and peer at our screens. Who could step out of the past, don a pair of blue jeans and a T-shirt, and join us on the second floor of Evans Science Building?

Clearly, the first one to consider is Aristotle. For of the 1,425 pages of extant writings of the philosopher appearing in two volumes of the Britannica Great Books Series, 338 pages are, in fact, a data base of biology, and another 95 deal with human biology. Their data-base character stands out as one scans the titles: *History of Animals, On the Parts of Animals, On the Motion of*

This essay appears in The Thermodynamics of Pizza, by Harold Morowitz, published by Rutgers University Press © 1990.

(continued next page)

Animals, On the Gait of Animals, On the Generation of Animals. Down to the very last details, Aristotle tries to create a complete catalogue of all knowledge of animals. Surely he would warm to our idea of a great knowledge base drawing on all the data bases of biology.

Hippocrates, the contemporary of Socrates, would certainly be a candidate for our workshop. He collected and organized the knowledge of medicine of his time. His books (*Prognostic, Epidemics, On the Articulation*, and others) were sources of data from which he reasoned to formulate the rational management of patients. He would have welcomed any assistance that could have been called up from MEDLINE or generated by any of the diagnostic software programs. Galen would have joined his predecessor in this search for diagnostic clues.

I do not know if Euclid, Archimedes, Apollonius, and Nicomachus would have come to our workshop, but if they had, I'm sure they would have joined the artificial intelligence work group and engaged in the many discussions of how to structure data bases so as to derive the maximum knowledge from them. They, perhaps, would have been unsympathetic with our concentration on data and would have searched for more general principles. I suspect that these analytical mathematicians would have grown impatient with computer modeling.

Titus Lucretius Carus, whose interest covered an encyclopedic range, would, I image, have entertained himself scanning abstracts on a vast range of topics. He would have reveled in the retrieval programs and found vast realms of material to incorporate in a new version of *On the Nature of Things*. He might now, perhaps, be overwhelmed by the range of material he tried to include in his long poems.

As I dream on about the authors of the great books, the mind wanders even further, and I envision Michel Eyquem de Montaigne sitting in front of a personal computer. When I ask him about his presence at our meeting, he starts a long discourse (recalling his essays) about the advantages of word processing for a writer. "Such a tutor will make a pupil digest this new lesson, that the height and value of true virtue consists in the facility, utility, and pleasure of its exercise, so far from difficult, that boys, as well as men, and the innocent as well as the subtle, may make it their own; it is by order and not by force to be acquired." I think he is talking about user-friendly systems and nod my head in assent.

The thread that runs through the lessons of the ages is that we all share a desire to understand our world. In response to that desire, we use whatever tools are available. I am convinced that a grand new set of tools has become available. In the tradition of the greats of the past, we will employ them to build new understanding. With no disrespect at all to our predecessors, it should be noted that we are standing at only the beginning of human potential. That is what makes each age so exciting.

—Harold Morowitz

New Postdoctoral Fellows Join SFI Research Staff

Drawing from nearly 250 applications from throughout the United States and abroad, the Institute has selected four promising young scientists as Postdoctoral Fellows for the 1991–1992 academic year. They join researcher **Mats Nordahl** who is beginning his second postdoctoral year here in Santa Fe.

Tom Kepler comes to SFI following two years as a Postdoctoral Fellow in the neurophysiology lab of Eve Marder at Brandeis University's Department of Biology. "While at SFI my research aims are to study, develop, and utilize mathematical models of natural dynamical systems including, but not limited to, the nervous system," writes Kepler. "I am particularly interested in metamodeling and the study of relationships between models at various levels of both abstraction and description. While it is clear that intricate high-level phenomena, for example, cognitive processes, cannot be reasonably or profitably described solely in terms of elementary processes at the lowest level of description, I believe that careful mathematical attention to transformations in terms of description will prove invaluable to all successful investigations into the nature of complex systems." Kepler's published research has included work in theoretical neurophysiology, statistical mechanics and dynamics of spin-glass neural networks (from the viewpoint of theoretical physics), and nonlinear dynamics. He has also done unpublished work in the modeling of protein folding and natural selection.

Described as "a highly imaginative and creative researcher into complex systems," **Chris Moore**'s current research interests focus on characterizing the complexity of dynamical systems. It has been known for some time that many-degrees-of-freedom systems—such as cellular automata, neural networks, and other systems consisting of many interconnected parts—are capable of highly complex behavior. Beyond being merely "chaotic," they can be unpredictable even if the initial conditions are known exactly. Moore's doctoral thesis showed that even finite-degree-of-freedom systems are capable of this. One technique, albeit limited, for characterizing complexity in physical processes has been to extract sets of symbol sequences from their behavior, and then measure complexity by the "Chomsky" hierarchy of languages. In many cases, however, algorithmic programs seem more appropriate. Writes Moore, "The eventual hope for such an approach would be to answer the so-called 'Physical Church-Turing Thesis': are any physical systems capable of non-algorithmic behavior? Are quantum systems, for instance, capable of drastically reducing computation time for certain types of problems? Or is physics fundamentally computable? Other questions would be, What dynamical systems are capable of computation? What systems of interaction support life? These questions are currently too ill-defined to answer. But by providing us with formal analogues of intuitive concepts like 'computation,' 'algorithms,' and 'complexity,' mathematicians have empowered us to replace speculations with theorems and proofs."

Walter Fontana has been closely associated with the Institute; as a recent Postdoctoral Fellow at Los Alamos National Laboratory, he began continuing research collaborations with SFI workers Stuart Kauffman, David Lane, John Miller, and Peter Schuster. About his research interests he writes: "Diversity is one characteristic aspect of 'complex systems.' Yet while biology, the economy, language, and culture are each a good example of a complex system, they differ dramatically from each other in their diversity-generating mechanism(s). In the hierarchy of nature there is, in my view, one level where this endogenous generation of diversity appears in a clear-cut fashion for the first time: chemistry. Chemistry is the most 'elementary' level of nature that allows for an infinite variety of stable and diverse structures capable of manipulating each other. This is why chemistry is interesting. It is worthwhile to explore the logical consequences of such a mechanism, given that it led within a large collection of molecules to the emergent state(s) we call 'early life.' As a first step in understanding complex systems of the diversity-generating kind, we need models that get rid of everything but the putative key ingredients. We call such models 'artificial worlds.' We then 'run' those worlds, hoping that they synthesize emergent phenomena. From this type of 'experimental mathematics' (as, I think, Stan

Walter Fontana (right), SFI postdoctoral fellow, in discussion with Peter Stadler, Max Planck Institute. Photo by Cary Herz © 1991.

Ulam put it) we hope to get clues for the formation of those concepts that are required to produce theories of the phenomena. In my work I focus on a rather abstract artificial chemistry where the molecules are symbolic computer programs. A program gets as input another program, manipulates it syntactically, and produces a new program. If we consider a large collection of them as 'colliding' randomly with each other, then any newly generated program can again act on other programs that are present in the ensemble, thus spawning new 'reactions,' and so on. This is the core idea of Algorithmic Chemistry or 'AlChemy.' Clearly, a conventional programming language is not well suited for expressing these programs. One has to go back to the mathematical foundations where a 'program' is a 'computable function' and where such functions can be represented in a clean symbolic system. It turns out that the most transparent and useful representation is the so called λ-calculus, a symbolic system that is equivalent to Turing machines, and that can be specified with a few axioms. One strength of AlChemy is the easy introduction of constraints that limit interactions among program-strings. At SFI I will study how different kinds of constraints, like spatial networks, the syntactic 'shape' of programs, computational limitations, and the like, generate different kinds of stable collective architectures. Applications aiming at understanding the topology of bacterial metabolisms, as well as applications to evolutionary biology, are being attempted."

Fontana will be in residence at the Institute as a Postdoctoral Fellow through September, 1992, when he moves to the Institute for Advanced Study in Berlin.

David Wolpert joins the Institute postdoctoral research staff supported by a fellowship from the National Institutes of Health. Wolpert, most recently a postdoctoral fellow at Los Alamos National Laboratory (and a 1988 Complex Systems Summer School alumnus), describes his research interests as revolving around the question: "If you're given a set of samples of input-output mapping, how should you generalize from those samples to infer the entire mapping? This question, sometimes called the problem of 'supervised machine learning,' touches on many disciplines, most obviously statistics, approximation theory, pattern recognition, classification theory, information theory, neural networks, and the AI problem of inductive inference. In fact, a solution to this problem is probably crucial since presumably it will never be possible to delineate by hand all of the aspects of a system's behavior necessary for that behavior to be intelligent. Therefore, to construct an intelligent program it will be necessary to have that program generalize from a core set of explicitly formulated input-output information. This question of how best to generalize is also none other than the question of how best to infer a theory (i.e., an entire input-output mapping) from some experimental data (i.e., from some samples of that mapping). From this perspective the problem of deducing an optimal generalizing algorithm is natural science's version of Hilbert's ill-fated program for algorithmically codifying mathematics. Either enterprise, if successful, would take humans out of the loop." Wolpert has developed two machine-learning techniques, "fan generalizers" and "stacked generalizations," which play a large role in his research. Part of his work at SFI will involve applying these techniques and others to the analysis of DNA and amino acid sequences. Such applications may suggest future experimental research in the associated areas of molecular biology by empirically discovering correlations and relationships among the set of features.

Finally, we're pleased to acknowledge once more the significant contributions to the Institute's research by its two inaugural Postdoctoral Fellows, **Martin Casdagli** and **Wentian Li.** Casdagli, whose work at SFI since 1989 has focused on the theory and application of nonlinear time-series forecasting, has decided to pursue his research activities in the private sector at FB Tech Joint Venture. Li's research at the Institute has centered both on the study of dynamical systems with many degrees of freedom and on the phenomenon of 1/f noise; this Fall he takes up a Postdoctoral appointment at Rockefeller University.

Art and More

One of the Institute's wishes—for art to enliven and personalize the somewhat bare interior of the Pecos Trail Building—has come true! Thanks to Santa Fe artist Morgan Thomas, our walls are now graced with more than 30 pieces of wall art, on loan from Thomas' fine collection of contemporary work. Local artists who loaned work include Linda Montoya, Anne Farrell, and Amy Pilling. Thank you, Morgan and friends, for this gift to our eyes and spirit.

If you would like to make a donation of furnishings, art, or other items, please contact Barbara Hodges at 505-984-8800.

Ruminations from a Corner Office

It's now the end of July, and nearly all the boxes have been unpacked at our new quarters. The white boards are up and once again covered with largely unintelligible scrawl; dirty coffee cups stagger across the table in the large conference room, and the nocturnal skirmishes for the good ergonomic chairs—forever in short supply—are matter-of-fact. The alarm system already has been set off twice, both times in the same weekend. In short, we're settled. Response to the new place is unexpectedly positive. I say "unexpected" because despite the many site visits and review of prospective layout plans none of us—staff and researchers alike—really knew what to expect about life after the Cristo Rey convent, our home since 1987. In any case, the thick carpeting, large well-lit offices, and general spaciousness of the new buildings is all and all startlingly comfortable, and everyone seems pleased. I write this in my large, private, corner office—large enough to house at least one Third World family comfortably—feelingly mildly disconcerted by the silence. I'm accustomed to an office-mate, two shrill telephones, and constant interactions with researchers—all in an office the size of a closet. Don't get me wrong: I like it—but suffering from residual sensory deprivation, I sometimes sneak upstairs to the research offices for a cup of coffee in hopes of some action.

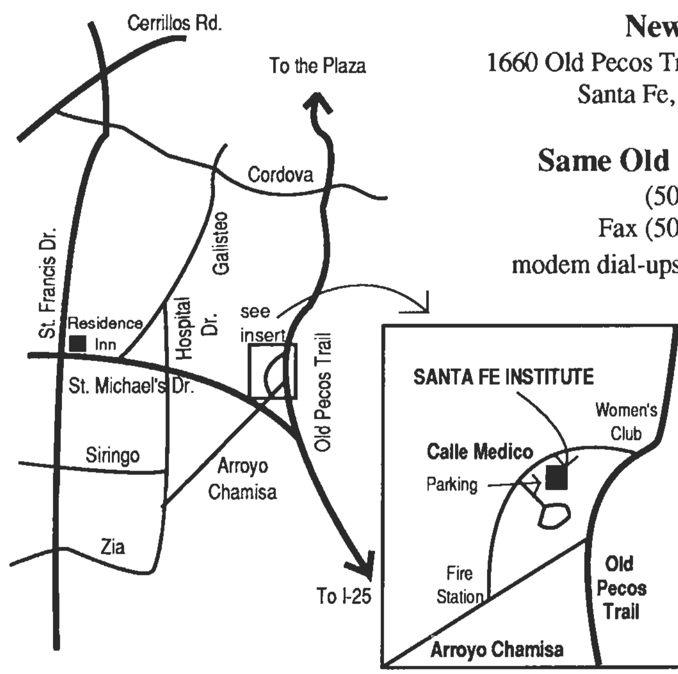
Although we're all quickly adapting to the new space, everyone agrees it lacks the quirky charm of the convent. I suspect the convent will become, in fact is, rapidly fading into those halcyon "early days" of SFI. Like a couple fondly recalling their starter home furnished with cinder block bookcases—or Senior Fellows discussing the old days at Los Alamos—SFI's nascent years on Canyon Road will come to hold special significance.

But the convent deserves celebration by virtue of more than nostalgia. From the moment we moved in, we recognized it as unique. Actually, some part of what made the building special was just the thought of it. Once home to a cloistered community, the building for me at least always retained an aura of indelible mystery which lingered long after its doors were opened. (Indeed it was not uncommon for middle-aged adults, long-ago students at the Cristo Rey school, to shyly knock on the convent door to finally "look inside.") A more provocative characterization of the building invoked science and religion, this a juxtaposition much favored by journalists. "Warm light from stained glass windows illuminated a wall covered with scientific scribbles. Computers and research fill the nun's quarters..." runs a recent description from the Associated Press. In fact our relations with the Archdiocese of Santa Fe, from which we leased the corner site, were cordial in every way, with neither party finding the partnership particularly unusual or philosophically trying. Still, the notion of science in the convent is piquant. And what more appropriate community than the Institute to be enamored by a concept?

But it was in working in the convent that we fully came under its spell. First, there was the utter beauty of it—the intricate ceiling of latillas in the small conference room, the sun-dappled patio with the carvings in the old trees, the lovingly crafted doors, polished mantels, and, yes, the stained glass windows. But its Spartan aspects were also right. Creased linoleum floors, Eisenhower-era kitchen, and precise office cubicles (they had been bedrooms) were almost collegiate, lending an ambience that seemed utterly appropriate to the Institute's endeavor. Eyes closed, the sweet odor of floor wax ever present, one could be in any physics department; open them to the beauty of the Jemez Mountains beyond the patio.

The building is laid out in an endearingly eccentric fashion, curiously shaped like a J (after the Sisters of St. Joseph I've been told). Did the oddness of the convent's plan encourage our unconventional thinking? I like to think so. Administrative offices were strewn about the building—you had to walk though the President's Office to get to the kitchen—and newcomers often had difficulty

We've Moved!



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Rumina-tions (cont'd.)

refinding the front door once they had entered the building. The convent's design anomalies were compounded by the fact that as the Institute grew we were increasingly desperate for space. Our Comptroller worked in what had been a laundry room; the Executive Assistant's desk was in a hallway; and boxes of books and computers invariably spilled from closets and corners. Yet oddly enough the building's design flowed gracefully; indeed it gently encouraged lots of informal interaction between staff and researchers. Even the long, narrow "Research Wing" worked although I can't explain why. In the most "linear" of environments a warren of collaborations flourished. Five offices lined each side of the dark corridor, linked by computer cable threaded through holes in the walls. A child's toy telephone, the kind made of cans and string, comes to mind when I think about the Research Wing. At either end of the corridor were staff offices—the orange juice cans as it were—linking the researchers to the outside world. Between, a sort of magical communication transpired, never to be logically understood.

Beyond the lineaments of a structure, of course, it is people who contribute to the unmistakable signature of place. For the SFI family at least, I am convinced much of the attractiveness of the convent was colored by the interactions of individuals and ideas, especially during our exhilarating first four years as we transformed ourselves from dream to reality. I'll always remember, for instance, the euphoria which permeated the first economics program meeting in 1987, the physicists and economists happily incredulous that they were actually communicating with each other. The students from the Complex Systems Summer School also come to mind; every June they flooded the building each afternoon after their classes at St. John's, scanning the library, accessing the network, and talking to our researchers. From their excitement you'd think they'd found Nirvana. Nor will I ever forget Buz Brock, a formidable economist and also a mean tap dancer, doing a slide shuffle down the long research corridor. Terrific. For me such experiences are indelibly mixed with the spirit of place at 1120 Canyon Road.

Did the charm of our first home—that beautiful, odd cluster of cells—shape our nascent SFI family? Lawrence Durrell in *Spirit of Place* argues that character is ultimately a function of landscape, and I'll warrant architecture qualifies as "landscape." If so, we are indeed indelibly marked by our years in the convent—imbued not only with its appealing spirit of "otherness" but also with the broad sense of history and culture it provides. Now, however, it's time to move on—to attend to the burgeoning responsibilities of a growing organization symbolized by this large office. The challenge is provocative.

But the sound of tap dancing still resonates in my ear.

—Ginger Richardson

Forrest Awarded PYI Honor

Stephanie Forrest, University of New Mexico. Photo courtesy of UNM.

SFI External Assistant Professor Stephanie Forrest was recently awarded a prestigious Presidential Young Investigator Award by the National Science Foundation. Forrest, who is an Assistant Professor of Computer Science at the University of New Mexico, was selected for her research on emergent computation and computational models of the immune system, described in more detail in this issue. The awards fund science and engineering research; recipients can receive up to $100,000 a year for five years in a combination of federal and private matching funds.

Forrest earned her Ph.D. in computer and communication sciences from the University of Michigan in 1985, where she also earned her master's in the same department in 1982. She earned her B.A. from St. John's College in Annapolis, Md. and Santa Fe, in 1977.

Before joining the UNM faculty in 1990, she was a Director's postdoctoral research fellow at the Center for Nonlinear Studies, Los Alamos National Laboratory. From 1985–1988 she was a scientist for Teknowledge, Inc., in Palo Alto, California.

As well as serving as a SFI External Faculty member, Forrest is on the editorial board of the *Journal of Experimental and Theoretical Artificial Intelligence*. She is a member of the Computer Professionals for Social Responsibility, the Institute of Electrical and Electronics Engineers, and Sigma Xi national honor society. In addition to publications in several technical journals, she is the author of *Parallelism in Classifier Systems* (Pitman Publishing, London, 1990) and recently edited *Emergent Computation.*

An article about Stephanie's research, and her collaborations with other SFI researchers, appears on the next page.

Emergent Computation and Learning from Nature

Introduction

The process of evolution has driven biological organisms to discover extraordinary computational solutions to the problems of survival. The body's immune system, for example, continuously solves a complex pattern-recognition problem in a manner rivaling the capability of today's supercomputers. In contrast to most computers' sequential and centralized programming, the immune system uses a parallel and distributed approach that appears to offer several advantages over standard computing methods. This form of computing, called "emergent computation," is seen in many biological systems created through evolution—and in the process of evolution itself.

How can the mechanisms of evolution and emergent computation be used to improve the capabilities of human-made computer systems? Stephanie Forrest of the Santa Fe Institute is pursuing the answer to that question.

Genetic Algorithms

A genetic algorithm is an idealized computational model of evolution based on the principles of genetic variation and natural selection, pioneered by SFI External Professor John Holland. The goal of a genetic algorithm is to find a good solution to a problem by evolving a population of solutions. Individuals in the population are represented as bit strings, collections of ones and zeros, corresponding to the chromosomes of biological organisms. During each generation the fitness of all individuals is evaluated; the best individuals tend to survive and produce new bit strings, while the less-fit individuals tend to be eliminated from the population. Through time the average fitness of the population increases, resulting in better solutions.

At each generation new bit strings may be produced either by mutation (changing a bit value) or through the crossover operator which combines two individuals to produce two new, mix-and-match offspring. Crossover allows two bit strings to combine and, in a single step, occasionally produce a much better offspring with the best features of both parent bit strings. For this ability to leap across to better solutions, the crossover operator is often credited for genetic algorithm's successful results.

The genetic algorithm, like evolution, exhibits the parallel and distributed behavior of emergent computation systems. The fitness of individuals, for example, can be evaluated in parallel during each generation. Responsibility for crossover and mutation is distributed among all individuals, rather than being given to a central authority. Each individual performs these operations autonomously. The behavior of the genetic algorithm is emergent because, while each bit string may mutate and crossover independently, it is the combined action of the entire population that produces results.

While inspired by the process of evolution, the genetic algorithm is actually a more general tool for studying adaptive systems and alternative models of computation. The next generation of computers may perform computation in a completely different manner because of the development of systems like the genetic algorithm.

Classifier Systems

Forrest has also worked on "classifier systems" which combine the genetic algorithm with rule-based reasoning—a style of programming popular in artificial intelligence research. A set of classifiers (rules) specified how the system would perceive external stimulus and how to compute a reasonable response to that stimulus. The genetic algorithm provided a mechanism for discovering new and better rules, allowing the classifier system to incrementally learn and improve its behavior with respect to the external environment.

Forrest's doctoral dissertation showed how cognitive structures could be implemented in a classifier system. In addition to simply responding to an external stimulus, a classifier system could now store complex information in the form of a semantic network. This proved that classifier systems could perform high-level reasoning like any other artificial intelligence system. But whereas standard rule-based systems were limited to the information supplied by the programmer, classifier systems can theoretically collect increasingly more information through the application of genetic or other algorithms. Classifier systems and other machine learning studies may provide the results needed to finally open the way to artificially intelligent machines.

Theoretical Aspects of the Immune System

We can never stop learning from nature.

In work with Alan Perelson of Los Alamos National Laboratory, also a member of the SFI External Faculty, Forrest has begun to model the immune system's adaptive response to invading molecular agents. While modeling the immune system is interesting from a biologist's perspective, Forrest sees this work as an opportunity to learn from nature and extend the capabilities of the genetic algorithm itself.

The purpose of the immune system is to recognize foreign agents in the body, called antigens, and create an effective response to that threat. A foreign molecule is recognized by using another molecule, called an antibody, which has the correct shape to bind with the foreign invader. Antibodies fit with antigens in a lock-and-key arrangement. It has been calculated that the immune system can recognize as many as 18 billion different antigens, which implies the need for 18 billion antibody molecules. But each antibody needs to be coded as a gene somewhere on the human DNA chain, which encodes only a million or so genes, and only a small portion of those can be used for the immune system. The solution to this paradox came in realizing that each gene did not always represent one molecule. In the immune system, genes from five separate "libraries" on the DNA chain are combined together in order to generate an antibody molecule from the combined code. Using this combinatorial approach the immune system is able to generate 18 billion antibodies with as few as 300 individual genes.

The diversity of the gene libraries, as with all aspects of the immune system, was created due to evolutionary pressures. Forrest and Perelson are exploring the genetic algorithm's ability to develop the recognition abilities of the immune system. The difficulty is that the standard genetic algorithm is designed to find a single best solution rather than a set of solutions, such as the set of all possible antibodies. By finding a reasonable genetic algorithm model of the immune system, Forrest has extended the capabilities of the genetic algorithm to similar problems with more than a single optimum point.

The Royal Road

Although it has been successfully applied to many problems since its invention more than fifteen years ago, the genetic algorithm and its behavior remain only partially understood. There is no comprehensive theory that relates characteristics of a problem directly to the performance of the genetic algorithm, or that predicts what the genetic algorithm's performance will be on a given problem. Much of the work in genetic algorithms has been based on what Forrest calls "folk theory," ideas and equations that have not been proven in general. Forrest, in collaboration with Melanie Mitchell of the University of Michigan, has been working to characterize the genetic algorithm in a formal theory that will explain why it works and for what type of problems it is best suited.

Forrest and Mitchell are developing a set of test functions, called Royal Road functions, with which to probe the workings of the genetic algorithm. These functions allow the experimenter to design problems that exactly emphasize the characteristics needing to be tested. Some problems are difficult for the genetic algorithm because they exhibit multiple local optima, deceptive information, space-sampling errors, or a combination of these and other features. In order to characterize the difficulties associated with each of these features, it is necessary to isolate their effects and analyze them separately. The Royal Road functions provide the experimenter with specific control over which features will be present in a given problem.

As the strengths and the weaknesses of the genetic algorithm become better defined, it should be possible to adjust and improve the effectiveness of the genetic algorithm based upon the characteristics of the problem to be solved. The Royal Road studies will also be used to develop a set of statistical tests for predicting the genetic algorithm's performance on different classes of problems.

The Future

While there is much work to be done on the immune system and the Royal Road studies, Forrest is already looking towards the future. Computers will grow more and more complex; even now, she says, they exhibit many properties of natural complex systems. Both natural and artificial computational systems must respond to real-time constraints, and be capable of adapting their behavior continuously to dynamic environments. Forrest believes that the converse is also true: that adaptive mechanisms must play a central role at many levels of computer design. A computational analog to the immune system, for example, may someday be needed to detect and fend off computer viruses and unauthorized users. Approaches such as these, rooted in the principles of evolution and adaptation, will be needed if we are to utilize large-scale and highly complex computing environments effectively.

—Ron Hightower

Ron Hightower is a Ph.D. student in the University of New Mexico Computer Science Department and a member of Stephanie Forrest's Adaptive Research Group.

Read On

The Dreams of Reason: The Computer and the Rise of the Sciences of Complexity
by Heinz R. Pagels

> Science has explored the microcosmos and the macrocosmos; we have a good sense of the lay of the land. The great unexplored frontier is complexity.
>
> —Heinz Pagels, *The Dreams of Reason*

Two of the most remarkable developments of twentieth-century science have turned out to be inextricably linked: the invention (and truly meteoric ascent) of the electronic digital computer, and the unfolding of a new group of scientific efforts aimed at discovering the laws governing physical, biological, and cultural systems of enormous complexity. What these efforts are, and how the computer has shaped them and the new world view they are producing is the subject of physicist Heinz Pagels' last book, *The Dreams of Reason.* Pagels, whose research made significant contributions to a number of areas in physics, was not only a highly prominent member of the scientific community—serving both as an associate professor at Rockefeller University and as Executive Director of the New York Academy of Sciences—but was also a prolific writer of books and articles on science for the lay public, as well as a committed campaigner for human rights around the world. Pagels' distinguished career ended tragically when he died in a mountaineering accident in Colorado in 1988, the same year *The Dreams of Reason* was published. This book, perhaps more than any of his other popular works, demonstrates the extraordinary range of his scientific and philosophical interests, and the degree of excitement he felt about new developments at the frontiers of science .

Pagels' purpose in writing this book was no less than to prepare the world for the coming revolution brought on by the new-found abilities of science to tackle and master complexity. He writes, "I am convinced that the nations and people who master the new sciences of complexity will become the economic, cultural, and political superpowers of the next century. The purpose of this book is to articulate the beginnings of this new synthesis of knowledge and to catch a first glimpse of the civilization that will arise out of it."

The "new sciences of complexity" include both novel approaches in traditional disciplines such as economics, neuroscience, psychology, and biology, and truly new areas of research that do not fit easily into established scientific boundaries, such as artificial intelligence and cognitive science, chaos theory, and artificial life. The three main themes of the book, at least as promised in the Introduction, are the rise of these new sciences and the synthesis that they are providing; the role of the computer in the development of these sciences; and the effects of the resulting reordering of knowledge on long-standing philosophical questions. I found the prospect of such a book very exciting indeed; at this point in the development of the sciences of complex systems, nothing is needed more than a clear framework for thinking about how these various systems are related and how computers are being used to gain insight into the workings of and relations among such systems. However, though the book contains much that will be of interest both to scientists and to lay readers, I found the overall result disappointing.

The book is in two parts, the first on "The Sciences of Complexity" and the second on "Philosophy and Antiphilosophy." The two parts seem almost entirely unconnected, as though two separate books were bound together.

Part I consists of a survey of some of the main ideas in the study of various complex systems, and of some of the major ongoing research efforts. In these chapters, Pagels discusses what he sees as the main themes underlying all these efforts: the use of biological organizing principles, such as variation and selection, in understanding systems in different disciplines; an emphasis on parallel networks as a unifying framework for complex systems; the importance of nonlinear dynamics and chaos in thinking about complex systems; a computational view of mathematics and physical processes; and the notion of the computer as a new way of probing natural systems, extending the traditional "theory" and "experiment" division of science. Pagels has done well in choosing these general themes to explain what the sciences of complexity are all about, but the book manages to treat these themes only at a fairly superficial level.

For example, a major theme is that the computer "is altering the architectonic of the sciences and the picture we have of material reality." This is happening in two ways: computers are being used as modeling or simulation tools that provide views of complex systems that could not be easily obtained through direct experimentation on the real systems, and also the notion of computation itself is being adopted as a principle for understanding the laws governing such systems. Pagels discusses these two notions and gives some examples, but the book tends to favor breadth over depth, and does not go very deeply in explaining what these two notions actually mean. This is disappointing, because these are very subtle ideas that need careful explanation. The notion of a computer model is absolutely central to modern science, and yet what a computer model is, what a mathematical model is, how they are different, and how they might produce different insights, remain obscure to most lay readers, for whom I assume this book was intended. The book contains many intriguing statements such as "Computers, because of their capacity to manage enormous amounts of information, are showing us new aspects of social reality," but never goes much deeper than that in describing what new aspects are being shown, and *how*.

What the book lacks in depth in its discussions of these issues, it makes up for in breadth. Pagels covers a very wide range of interesting topics, though in a somewhat disjointed way. The first chapter of Part I is an overview of the main themes of the book. We are then taken at lightning speed through a survey of different attempts at defining the notion of "complexity," and then through nonlinear dynamics and chaos theory, from which we jump to an overview of several different computer simulations of complex systems, after which a chapter is devoted to discussing connectionism and neural nets (in somewhat more depth than is devoted to the previous topics). (Throughout Part I there are several mentions of the Santa Fe Institute and SFI-affiliated scientists.)

This book is obviously the work of a highly diverse mind. Within the space of a few pages, Pagels can jump from selective systems as a bridge between disciplines, to selfish genes, to sociobiology, to problems in synthesizing biology and social sciences, to artificial life. None of these topics is given much more than a paragraph or two, and it is often hard to keep up or to get a clear sense of any of these issues if one doesn't already know much about them. I enjoyed the range of the book, but was constantly frustrated by the lack of depth. There are many tantalizing throwaway lines, such as the following: "But in fact, nature can be viewed as an analogue computer." Or, because of the notion of "selective system...it may, in fact, now be possible to develop a science of society that is minimally distorted by the political and social values of the investigating scientist much as is the case in the natural sciences." Or, "Chaos isn't just a meaningless jumble. In fact, it may be possible to detect the statistical regularities in chaos provided that chaos is used as a probe." These remarks are suggestive, provocative, and demand further explication, but often we are left hanging on the edge of our seats. I found myself constantly wishing that more would be said on a particular topic, but was hardly ever satisfied. In general, too many topics are covered at too superficial a level.

The second part of the book (which seems almost like an entirely different book) is a collection of essays on various philosophical issues that are related to modern science, such as the mind-body problem, the nature of mathematics, and the characterization of scientific activity. The title of the book doesn't really apply to Part II, since these essays do not directly bear on computers or complex systems. There is, however, much of interest here, for those who enjoy thinking about classic philosophical questions such as "Are mathematical objects real?" or "What is the nature of consciousness and free will?" Pagels combines a survey of philosophical thought on these questions with his own musings, anecdotes, recountings of conversations with friends and neighbors, childhood reminiscences, etc. The style is quite rambling, disjointed, and somewhat repetitive—this book is not strong on crisp organization or on sticking to a point—but these essays are nonetheless fun to read, often very thought-provoking, and sometimes rather irreverent. Much of Pagels' obviously strong personality shines through, as in one anecdote that will raise many hackles: He almost gleefully reports expressing the following opinion (that resulted in shocked silence) at a party with a number of writers, editors, and other intellectuals of humanistic bent ("not a scientist in the group except for me"): "It is difficult for me to remember people's opinions (even my very own). What I remember are concepts and facts, the invariants of experience, not the ephemera of human opinion, taste, and styles. Such trivia, are not to be considered by serious people, except as intellectual recreation."

Throughout Part II is the theme of Pagels' strong belief in the reality of the referents of scientific theories: "The invariant order of nature that is expressed in our theories—the cosmic code—is possible because the material world is actually organized in that way." He is clearly very interested in philosophical questions about whether or not scientific theories are discovered or invented, and while he attempts to reconcile these two views, he comes down squarely on the side of discovery: "This is perhaps the most socially and culturally distinguishing feature of science—it is universal in the sense that its truths are truths for everyone."

What does all this philosophy have to do with complex systems and computers? Connections between Parts I and II of the book are not made, at least not very clearly. The second-to-last chapter, with a fairly brief discussion of scientific instruments and how they affect science, finally comes back to the computer, saying once more, "The computer, the instrument of the sciences of complexity, will reveal a new cosmos never before perceived," but does not go into much detail about how it will do so. A clear account of the many ways in which computers and the sciences of complex systems have been fundamentally linked, and how this has changed (and will change) the way scientists think was what I was most hoping for in this book, and though the book was enjoyable and stimulating in many ways, this hope was ultimately unfulfilled.

But in spite of the imperfections and the often frustrating lack of depth, I would recommend this book for those who want a broad overview of the frontiers of complex systems research or an introduction to some of the major questions in philosophy of science and mathematics. There is much here that will provoke any reader's interest, and will leave one wanting to learn more. *The Dreams of Reason*, along with his other books and articles, serve as a legacy of Pagels' broad interests and commitment to sharing his tremendous excitement about science with the general public.

—Melanie Mitchell

Melanie Mitchell is a faculty member in the Electrical Engineering and Computer Science Department at the University of Michigan.

Activity Update

Adaptive Computation

"The Institute has targeted our program in adaptive computation for major expansion this year and beyond," says President Ed Knapp, "and I am deeply gratified that an ever-growing number of our funding sources have recognized the vital importance of this effort in relation to SFI's central research objectives." Indeed, it has become increasingly clear over the past several years that the study of adaptive computational systems is proving to be a major cornerstone in the effort to understand complex adaptive systems (CAS). It promises not only a deeper insight into the nature and consequences of CAS, but also the application of these lessons to the creation of a new generation of computer-based systems endowed with advanced adaptive abilities.

To encourage the program's transition to a full-scale research effort, SFI will be holding a Founding Workshop in the Spring of 1992, supported by the Alfred P. Sloan Foundation. The goal of that meeting is to create additional viable research networks, identify some "flagship" problems of interest to the Santa Fe Institute, enhance the base of researchers and projects, and provide the necessary impetus for a residential program.

During the first part of 1991 the Institute's work in this area has been by no means idle. Indeed, several new projects have been begun. The SimToolKit is a recently initiated collaboration between Simulations Laboratories in Northern California, and SFI in the creation of new simulation software authoring tools and techniques. Simulation of complex systems is an important part of SFI research, and Simlabs is involved in research and development of software and tools that emphasize graphical user-interfaces, user-friendliness, sophisticated data visualization techniques and powerful simulation technology. An August workshop "Simulation Authoring Tools and the SimToolKit Project," chaired by Simlab's James Kalin, brought together researchers to report on practical problems and opportunities in simulation software development with the end of creating an R&D network as well as a set of specific objectives for the SimToolKit project.

Another new component of the SFI Adaptive Computation program is the "Audification" project, described in greater detail on page 16 of this issue. Audification refers to the use of changes in sound to "display" the status of a multi-dimensional system. SFI researcher Gregory Kramer is developing this technique to contribute to scientists' ability to comprehend complex dynamical systems and large-scale data sets. Kramer is also working with Arizona school children on an audification project funded by Apple Computers and sponsored through the Institute.

A number of other SFI researchers are involved in projects relating to Adaptive Computation. SFI External Associate Professor Stephanie Forrest's work is described elsewhere in this issue. One of the most important tools for building adaptive computational models is genetic algorithms. Forrest, along with SFI visitor Melanie Mitchell, Assistant Professor of Computer Science at University of Michigan, are making fundamental progress on developing a general characterization of those classes of problems for which genetic algorithms are best suited.

Funding provided by the Maxwell Foundation for the Robert Maxwell Professorship in the Sciences of Complexity has been vitally important in furthering the Institute's research into adaptive computation, by providing support not only for the chair itself but also for associated research by younger scientists who come to the Institute to collaborate with the Maxwell Professors. 1991 Winter/Spring occupants of the chair were Stuart Kauffman, Professor of Biochemistry and Biophysics at the University of Pennsylvania, and David Pines, Professor of Physics at the University of Illinois. Maxwell Visiting Fellows were James Crutchfield, Physics, University of California at Berkeley; Alfred Kubler, Physics, University of Illinois; and John Miller, Social and Decision Sciences, Carnegie-Mellon University.

University of Michigan/SFI Collaboration

In an effort closely related to the adaptive computation program, the Institute last fall began a joint SFI/University of Michigan project to develop techniques capable of modeling parts of real systems involving human societies—methods of practical use to working policy-makers. This effort is funded by the Joyce Foundation in addition to support by SFI and the University of Michigan.

The initiative, in fact, has a double goal: the first is to develop a policy-makers' tool kit through collaborations involving Michigan faculty, generally from the social sciences, and SFI members, who will primarily bring expertise in the mathematical and computational modeling of complex systems. Within this collaborative process is the project's second aim: to explore the prospects and nature of research exchanges between SFI and university communities.

On the Michigan campus this past winter John Holland taught a graduate level course on complex systems, and four alumni of this program participated in this year's Complex Systems Summer School. Concurrently, the process of integrating Michigan scholars into SFI research, begun in 1990, continued with a series of Santa Fe visits by Michigan faculty. Melanie Mitchell's work with Stephanie Forrest is described in this issue. Another visitor was Richard Nisbeth, Director of the Institute for Social Research. Nisbeth, a psychologist, described to SFI researchers his work on differences in reasoning strategies. He found common interests with, among others, David Lane on reasoning and organizational management; with Stuart Kauffman on heuristics, optimizing, and limits on the value of look ahead in modeling; and with John Geanakoplos and Lane on "mast binding" procedures in the determination of preferences. As a direct result of his visit to SFI, Steven Pollack, Professor of Industrial and Operations Engineering, is arranging to spend a portion of his 1991-92 sabbatical leave in residence at the Institute. During Charles Sing's visit here, this Professor of Human Genetics explored the overlaps between genetics and economics; the potential of genetic algorithms for modeling complex diseases and for identifying patterns in data sets; and the applicability of rugged-landscape models and models of adaptation at the edge of chaos for describing the evolution of human diseases and the health-care delivery system. John Jackson, Professor of Political Science, collaborated extensively with members of the Economics program, focusing on the common interests between his work on political and economic institutions and SFI research on adaptive models.

In November a second annual SFI seminar on complex adaptive systems will take place on the Michigan campus.

Life Sciences

In May, the Third Waddington Meeting on Theoretical Biology, chaired by SFI members Brian Goodwin and Stuart Kauffman, along with Franco Varela, Ecole Polytechnic, took place at the Institute. The Waddington meetings are organized as informal workshops involving a small number of participants in a week's intensive discussion. This meeting examined a range of biological examples that reveal, in different contexts, the basic self-generating and adaptive properties of living systems. A volume based on research discussed at this meeting will be available in 1992 as part of SFI's series.

Thanks to Alan Perelson's efforts, the Institute is increasingly known as a major center of activity in the field of theoretical immunology. Over the last eighteen months the TI program has issued six preprints/reprints in the SFI series. The mailing list of experimentalists and theorists interested in the program continues to grow. In 1991 TI activities accelerated, and throughout this year several visitors are in residence for extended periods of time. Catherine Macken, Stanford University, spent a month at SFI this Spring working with Perelson. Lee Segal, Weizmann Institute, and two of his graduate students, Eva Jaeger and Michael Fishman, were in residence in August. Additionally Brenda Javornik from the University of New Mexico is in residence at SFI on a long-term part-time basis, working with Stephanie Forrest and Perelson on a joint genetic algorithm-immunology project.

In October Wilfrid Rall, National Institutes of Health, will chair the workshop "Implications of Dendritic Neuron Models for Neural Network Properties." Actual neural networks are complex systems composed of biological neurons that are known to be significantly richer in their properties than the simple elements assumed by most network modelers. Some neuron modelers have already explored some of the implications of different spatio-temporal patterns of synaptic input to the large dendritic neuronal surface; some are now examining the effects of different distributions of various ion channels over the neuron surface; some are exploring implication of the various nonlinearities that are associated with these aspects of biologically realistic individual neurons. This meeting will focus on further exploring the functional implication of such neuron complexity for biological neurons and for realistic neuron models.

Economics

The Institute's Economics Research Program continued to operate at full speed during the first part of 1991 with workshop meetings taking place on almost a monthly basis. These meetings occurred in tandem with the work of the program's long-term residential researchers including Larry Gray and Ashok Maitra and with its several research networks which create the models and interpretative frameworks that give substance to the vision of the economy as a complex adaptive system.

As might be expected, the February meeting "Wall Street and Economic Theory: Prediction and Pattern Recognition," chaired by SFI Economics program co-directors John Geanakoplos and David Lane, generated much popular interest. One of the most famous claims in all of economic theory is that stock market prices follow a random walk. One implication is that no system of prediction or pattern recognition based solely on publicly available data such as past prices or volumes of trade (that is, without insider information) can yield predictions about future prices that would enable a trader to earn a rate of return greater than what is warranted by the risk he takes. The statistical evidence accumulated over many years has apparently borne out this "efficient market hypothesis," and as a result, technical analysis enjoys a dubious reputation despite the large number of its dedicated practitioners on Wall Street.

Needless to say, the inability of economists to find a pattern in financial market price processes may be the consequence of using inappropriate statistical techniques. At the meeting investment bankers and money managers from Salomon Brothers, Goldman Sachs, Kidder Peabody, Bear Stearns, Tudor Investments, Frontier Financial, and Panagora Asset Management pointed to evidence that technical analysis might be helpful, and some claimed that they were already using neural networks and genetic algorithms to make better than average returns on their investments. Economist Buz Brock argued that we now have proof of significant nonlinearities in stock market patterns which could have been recognized by conventional linear statistics. Physicists Doyne Farmer, Norm Packard, Richard Palmer, and Ed Jaynes, probabilist Stephen Levitson, and computer scientist John Holland all expressed confidence that techniques such as local nonlinear estimation, genetic algorithms and neural networks, entropy maximization, and classifier systems would uncover patterns in the data, if there were any. Moreover, some of them also indicated that preliminary studies with these techniques had revealed patterns in stock market data.

If there are patterns to stock market prices, what causes them? Economists have often argued that patterns are self-defeating and, as soon as they are recognized, efforts to exploit them will destroy the pattern. But, of course, this begs the question of heretofore undiscovered patterns, and it also raises the possibility that patterns collectively could be self-reinforcing: the effort to exploit one pattern might create a new and more obvious one. Three possible causes for patterns were suggested at the Santa Fe conference. First, it might be that a small group of clever people might actually know a great deal about the economy. When these few execute their trades, they may leave telltale tracks in the market. Others need not understand the market, but just follow these signs. On the other hand, group psychology may have a more potent and predictable effect on the market than economists have typically believed. Traders may go through predictable mood swings—the greed and fear cycle, as one Wall Street practitioner put it, in which, for example, they have a tendency to become aggressive buyers after a short run of good news, and nervous sellers after their "good luck" keeps going for an uncomfortably long time. If nonlinear analysis techniques uncovered such patterns, economists would have to incorporate

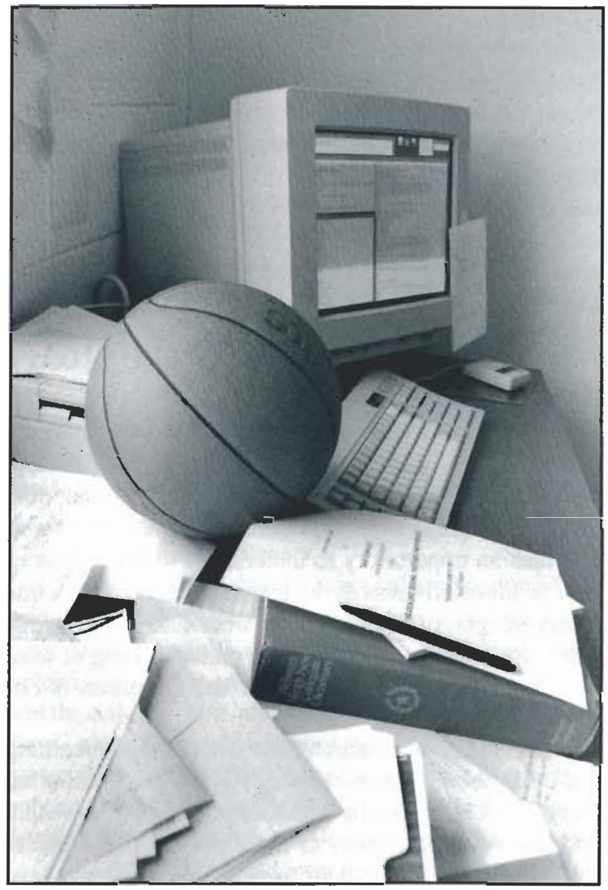

Photo by Cary Herz © 1991.

psychology into their models. A third possible cause for patterns in market data is the response of structural patterns in the economy that earlier statistical techniques have not allowed economists to notice. For example, suppose prices tend to fall faster than they rise (a conjecture that is still being tested). That might be an unintended effect of the use of collateral, or perhaps, in some still more important way, a result of how capital markers are organized.

To date, no published material has resulted from this meeting, although articles may be forthcoming. For results from SFI's ongoing meetings in all topic areas, check the listings of the Institute's books and publications which appear periodically in this Bulletin.

Two new economics research initiatives will start up this fall. José Scheinkman, University of Chicago, and Andre Shliefer, Harvard University will convene a "Growth in Cities" study group in Santa Fe in September. Many historians have argued that innovations occur primarily in cities. The cramming of individuals, occupations, and industries into close quarters speeds the flow of ideas between people and industries. It has also been suggested that these interactions between individuals in cities greatly facilitate technological advance. This dynamic view of cities fits nicely with much of the recent work on economic growth—work that views externalities (and especially externalities associated with knowledge spillovers) as the "engine of growth." If intellectual breakthroughs cross hallways and streets more easily than oceans and continents, then we should expect knowledge spillovers to be particularly important in cities. So the growth of cities provides a natural place to test these growth theories. Cities are both (1) particularly likely to be affected by these knowledge spillovers and (2) suitably plentiful to provide enough observations for serious statistical work on the theory of growth. They are one key to the understanding of technological development. But connecting cities with growth theory not only provides a useful testing ground for this theory, it also provides an opportunity to understand why some cities have plummeted towards poverty and urban crisis, while others prosper. By understanding what makes cities grow, there is the possibility for a better understanding of what caused (and what can remedy) the urban failures of our time.

A second new research node will center on learning and innovation in organizations. The initiative will bring together social scientists who study the dynamics within and between organizations; mathematicians, computer scientists, physicists and theoretical biologists who have developed tools to model complex adaptive systems; and "real-world" practitioners from industry and the public sector who have grappled with the difficulties of introducing innovation into the operation of large organizations. The purpose of the initiative is to develop theory and models for learning and innovating in the organizational context and to apply these models to a series of concrete problems arising out of the experience of organizations sponsoring the initiative. Some of the questions the initiative will address are the following: how organization structure affects what they can learn about their environment (internal and external); the organization of research and development: internal, shared, and contracted; incentives for innovation inside organizations: bureaucracy and competition; and external effects of innovation: networks of organizations and public impact. To begin, the Institute will convene a series of problem-oriented workshops, starting in 1992. The first, "Adaptive Processes and Organization: Models and Data," will be chaired by Michael Cohen, University of Michigan, and David Lane.

Sustainability

In July, 1991, SFI co-hosted with the World Resources Institute and the Brookings Institution a summer study group on "Visions of a Sustainable World." This was the latest and largest of a series of meetings by the three organizations aimed at formulating a joint project to attain a better understanding of how, and whether, humanity can make a shift to sustainability. The project would combine computer modeling and simulations with other studies, trying to develop new approaches to deal with the interlocking complexities needed to consider biophysical and human variables in a holistic, if crude, manner.

The participants agreed that the project would be difficult, that some parts of it might have relatively small chance of complete success, but that the project was nevertheless very much worth doing. Humanity is up against a severe time restraint; within the next 50 to 100 years it will begin to encounter severe biological and physical limits, compelling adjustments more drastic and rapid than human institutions may be able to make. Moreover, much is unknown about the interaction of human, biological, and physical systems, and certain interactions may create "cliffs" which are unrecognizable until one is at—or over—the brink.

The early part of the meeting was given over to substantive discussion of the concept of sustainability and its components, drawing on work underway at WRI on the transitions needed to move to a more sustainable future. These transitions cover the gamut of human activity from technological developments to broad questions of governance and ideology. The key variables in these potential transitions, the relationships among them, and the questions of their relative timing provide a basis for the substance of a long-term project.

Attention then focused on possible project methodologies. As currently envisioned, this three-year project would begin with the development of at least one crude "holistic" model, several simulations and scenarios, more in-depth analysis of a number of topics deemed critical, and possibly some theoretical work on modeling. Over the course of three years, all of these efforts would probably be substantially revised. The key to success lies in the project's ability to keep the various communities of researchers communicating with each other and to develop a number of approaches to the problem of sustainability.

Based on the substantial progress made during the summer meeting, the sponsoring organizations are now preparing a detailed project proposal for submission to funders in the next few months.

—Ginger Richardson

Colloquia: January–July, 1991

Social Evolution
Bob Artigiani, U.S. Naval Academy

Speciation by Simplicity or Controlled Diversity
Aviv Bergman, Stanford University

Entropic Uncertainty Relations
Iwo Bialynicki-Birula, Institute for Theoretical Physics, Poland

Desert Dynamics in Natural and Synthetic Systems
Tony Burgess, University of Arizona

Managing Complexity vs. Modelling Complexity—The Basic Research Gap
Roger Cox, Sandia National Laboratories

The Attractor-Basin Portrait of a Cellular Automaton
Jim Crutchfield, University of California, Berkeley

The High-Performance Computing and Communications Initiative
Charles Brownstein, National Science Foundation

The Physics of Roulette
Doyne Farmer, Santa Fe Institute

Computing with Structured Connectionist Networks
Jerome Feldman, International Computer Science Institute

Complexity and Bounded Rationality in Economics and Chess
John Geanakoplos, Yale University

Adaptive Behavior—A Partial Description of Robust Dynamics?
Brian Goodwin, Open University, UK

Fault-Tolerant Universal Cellular Automata (CA)
Larry Gray, University of Minnesota

Coding Structure of RNA Sequences & Self-Structuring as Substrate of Evolution
Pauline Hogeweg, University of Utrecht

Optimal Prediction in a High-Dimensional, Evolving Environment
Alfred Hubler, University of Illinois

Biosim—Game-Oriented User Interface for Alife Simulation
Ken Karakotsios, Algorithmic Arts/Maxis

Waiting for Carnot: The Search for Laws Governing Complex Adaptive Systems
Stuart Kauffman, Santa Fe Institute

Networks in Neurophysiology: Mathware for Wetware
Nancy Kopell, Boston University

Fractal Analysis for the Studies in Complex Systems
Alain Le Méhauté, Alcatel Alsthom Recherche, France

Mapping Psychoanalysis to Cognitive Science
John Lundgren, Los Angeles Psychoanalytic Institute

What Are Genetic Algorithms and What Can They Do For You?
Melanie Mitchell, University of Michigan

Unpredictability and Undecidability in Dynamical Systems
Cris Moore, Cornell University

Modelling Dynamical Phenomena in Motile Systems
Masatoshi Murase, University of California, Davis

The Versatility of RNA: Lessons from the Ciliate Tetrahymena
Henrik Nielsen, University of Copenhagen

Toward Agent Programs with Circuit Semantics
Nils Nilsson, Stanford University

Optimization and Creativity in Evolution
Tom Ray, University of Delaware

Beyond the Centralized Mindset: Learning to Think About Self-Organization
Mitchel Resnick, MIT

Replicator Dynamics and Beyond: Differential Equation Models of Complex Systems
Peter Stadler, Max Planck Institute, Göttingen

Dynamical Analysis of Biological Regulatory Net works: A Logical Method and Its Automatization
Denis Thieffry, Université Libre de Bruxelles

Mean Field Analysis of Systems that Exhibit Self-Organized Criticality
James Theiler, Los Alamos National Laboratory

The Immune System as a Dynamical Network
Gérard Weisbuch, Ecole Normale Supérieure, Paris

Stacked Generalization
David Wolpert, Los Alamos National Laboratory

Listening to the Ear
George Zweig, Los Alamos National Laboratory

In June, SFI added Tuesday lunch-time seminars on complex adaptive systems. This series of seminars and discussions will provide a forum in which those associated with the research programs of the Institute can discuss the various manifestations of complexity and adaptation and seek a deeper understanding of these phenomena.

Programs and Activities

FALL, 1991

Scientific Meetings

Sep 12-16	Workshop on Self-Organized Criticality *P.W. Anderson and Sidney Nagel*
Sep 27-29	Workshop on Growth in Cities *José Scheinkman*
Oct 10-14	Implications of Dendritic Models for Neural Network Properties *Wilfred Rall*
Nov 4-18	SFI/University of Michigan Adaptive Computation Meeting (Held in Ann Arbor, Michigan) *John Holland*
Nov 8-10	Harmonizing Economic Competitiveness with the Environment *Co-sponsored with the North American Institute*

Public Lecture Series

Sep 25	Growth in Cities: The Role of Diversity in the U.S. Urban Experience *José Scheinkman, Economics, University of Chicago*
Oct 9	Justice and the Human Genome: Social and Ethical Issues of the New Biology *Marc Lappe, Health Policy and Ethics, University of Illinois*
Nov 13	Thermodynamics of the Artificial *James Crutchfield, Physics, University of California, Berkeley*
Dec 4	Scaling in Nature *Geoffrey West, Theoretical Division, Los Alamos National Laboratory*

SPRING, 1992

Scientific Meetings

Jan 12-25	1992 Complex Systems Winter School (Held in Tucson, Arizona) *Peter Carruthers*
Feb 25-Mar 1	Resource Stress and Response in the Prehistoric Southwest *George Gumerman*
Feb/Mar	Theoretical Computation in the Social Sciences *Michele Boldrin and John Miller*
Jun 1-26	1992 Complex Systems Summer School *Lynn Nadel and Daniel Stein*
Jun 15-19	Artificial Life III *Christopher Langton*

Visitors: Jan–Jul, 1991

Bob Artigiani	U.S. Naval Academy
Tony Begg	Brunel University, UK
Aviv Bergman	Stanford University*
Hugues Bersini	University of Belgium
Tony Burgess	University of Arizona
David Campbell	Los Alamos National Laboratory*
John Casti	Technical University of Vienna
Francesca Chiaromonte	University of Rome*
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Murray Gell-Mann	California Institute of Technology
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Larry Gray	University of Minnesota*
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Dan Stein	University of Arizona*
Charles Stevens	Salk Institute
William Sudderth	University of Minnesota
Massimo Warglien	University of Venice
Andreas Weigend	Stanford University
Gérard Weisbuch	Ecole Normale Supérieure, Paris
Peyton Young	University of Maryland
Michael Zeilik	University of New Mexico

* One month or longer

Publications Update

We published 8 working papers in 1989 and 28 papers in 1990. We have already printed 31 papers in 1991; at that rate we could publish over 60 papers this year!

1990 Lectures in Complex Systems, edited by Daniel Stein and Lynn Nadel, Lectures Volume III is currently available. These are the lectures and seminars from the 1990 Complex Systems Summer School plus some student contributions.

Artificial Life II, edited by Christopher Langton, Chuck Taylor, Steen Rasmussen, and J. Doyne Farmer, Proceedings Volume X, also is available. This volume has expanded to almost 900 pages, including color plates. There is also a two-hour videotape which includes visual material from the workshop and some historical footage. It can be purchased separately or in a special package with includes a paperback copy of the book, the videotape, and a limited edition poster based on the poster design for the conference; this special package represents about a 20% savings over purchasing the videotape and volume separately.

Evolution of Human Language, edited by Jack Hawkins and Murray Gell-Mann, Proceedings Volume XI should be available in Fall, 1991. Based on a workshop of the same title, this volume includes an introductory chapter which ties together a wide range of papers and ideas.

Nonlinear Modeling and Forecasting, edited by Martin Casdagli and Stephen Eubank, Proceedings Volume XII, should also be available this Fall. The introduction to this volume will include brief bibliography of other reading pertinent to this field.

Four additional volumes have been scheduled to begin production in this year. These include:

- *The Global Dynamics of Cellular Automata: An Atlas of Basin of Attraction Fields of One-Dimensional Cellular Automata*, by Andy Wuensche and Mike Lesser, Reference Volume I, available November, 1991
- *Principles of Organization in Organisms*, edited by Arthur Baskin and Jay Mittenthal, Proceedings Volume XIII, available January 1992
- *Evolution of Southwestern Prehistory*, edited by George Gumerman and Murray Gell-Mann, Proceedings Volume XIV, available in early 1992
- *1991 Lectures in Complex Systems*, edited by Lynn Nadel and Daniel Stein, Lectures Volume IV, available May 1992

More than eight volumes are planned or under discussion for 1992. Once again, there are more requests to produce volumes than we have resources to handle. For more information about our series, please call or write to the Publications Department at SFI.

—Ronda K. Butler-Villa

We print a limited number of each working paper. They are available by mail request or in our library, free of charge. A list of papers with or without abstracts is available upon request to the Publications Office.

Board News

Erich Bloch. Photo by Morton Broffman © 1991.

William M. Keck. Photo courtesy of Coalinga Corporation.

Thomas F. Pick. Photo courtesy of Michael Metzger.

John G. Powers

The Institute welcomes the following new members to its Board of Trustees:

Armand F. Bartos currently serves as a consultant to Bartos & Rhodes Architects in New York, New York. Mr. Bartos is a member of the Trustee Committee for Architecture and Design and Vice-Chairman of the Trustee Committee for Painting and Sculpture of the Museum of Modern Art, New York. He serves on the Trustee Committee for Exhibitions at the New York Public Library. He is a co-founder and President of the Aspen Center for Contemporary Art, Aspen, Colorado. Mr. Bartos was elected a Fellow of the American Institute of Architects in 1974.

Erich Bloch is Distinguished Fellow for the Council of Competitiveness, a private organization to improve the country's competitiveness in the global marketplace. Prior to his appointment at the Council, Bloch was Director of the National Science Foundation, having been confirmed in that post in 1984. Before joining NSF, Bloch was Corporate Vice President for Technical Personnel Development at IBM Corporation which he joined in 1952 as an electrical engineer. In 1985 he was awarded the National Medal of Technology by President Reagan for his role in pioneering developments related to the IBM/360 computer that revolutionized the computer industry. In 1989 Bloch was the recipient of the IEEE United States Activities Board Award for Distinguished Public Service and the IEEE 1990 Founders Medal. He is a member of the National Academy of Engineering and is a Fellow of the American Association for the Advancement of Sciences and of the Institute of Electrical and Electrons Engineers as well as a member of its Computer Society.

Michael B. Campbell serves as an Attorney for Campbell & Black, P.A., in Santa Fe, New Mexico. He received his undergraduate degree in 1970 and his juris doctor in 1975 from the University of New Mexico. He was admitted to the Bar in 1975, New Mexico and U.S. Court of Appeals, Tenth Circuit. From 1975 to 1976, Mr. Campbell served as a Law Clerk to the Honorable Oliver Seth, U.S. Court of Appeals, Tenth Circuit. He was a member of the board of the Antitrust Section of the State Bar of New Mexico from 1983 to 1985 and is also a member of the American Bar Association. Campbell was elected Trustee and Secretary of SFI.

William M. Keck, II, has served as President of Coalinga Corporation, an independent oil company headquartered in Los Angeles, California, since 1973. He currently acts as Director and Vice President of the William M. Keck Foundation and President and Director of the William M. Keck, Jr. Foundation. A member of the Board of Trustees and member of the Executive Committee of the Southwest Museum, he has been a University of Southern California Trustee since October, 1979, and presently serves on the Audit, Academic Affairs, Development and External Affairs Committees as well as the boards of Harvey Mudd College, Good Samaritan Hospital, The Pacific International Center for High Technology Research (PICHTR), and The Dole Foundation for Employment of Persons with Disabilities. Mr. Keck is a Council Member for the California Council on Science and Technology.

Charles Miller is President and Chief Executive Officer of Transamerica Criterion Group, Inc. in Houston, Texas. He also serves as Chairman of Criterion Investment Management Company. Additional affiliations include: Chairman, Board of Trustees of the University of Houston Foundation; Board of Directors of Central Houston, Inc.; Board of Visitors of The University Cancer Foundation, M. D. Anderson; Council of Overseers for the Jesse H. Jones Graduate School, Rice University; Board of Trustees, Houston Museum of Natural Science and Planetarium; Board of Trustees of St. John's College and The Thomas Rivera Center; Advisory Committee for President, Texas Southern University; and Houston Private Sector Initiatives. Mr. Miller is currently serving as Chairman of the City of Houston Land Use Strategy Committee and Chairman of the State of Texas Educational Economic Policy Committee.

Thomas F. Pick currently serves as the Senior Vice President of Prescott Ball & Turben and President of Pick Associates in Chicago, Illinois. His previous posts include a directorship and presidency of George Pick & Co., as well as positions with Burton J. Vincent, Chesley, and A.G. Becker & Co. He has served as President of the Michael Reese Research Foundation and President of the Amherst Club of Chicago and is currently a member of the boards of the Michael Reese Hospital & Medical Center; Lifesource, a major Chicago blood bank; and the I Have a Dream Foundation.

John G. Powers is an attorney and business consultant currently residing in Carbondale, Colorado. In 1981, he received an honorary doctor of humane letters degree from Colorado State University. He joined Prentice-Hall in 1943 as General Counsel; and, in 1954, was promoted to President. In 1965, he founded the Aspen Institute Asian Seminars and Aspen Japan Seminar and is a lecturer on Asian thought and art. His affiliations include: Chairman, Board of Trustees, Aspen Center of Contemporary Art; Collections Committee, Denver Art Museum; East Asian Civilizations Visiting Committee of Harvard College; Fine Arts Visiting Committee of Harvard College; Chairman, Mid Valley Land Company; Director, Springer-Verlag New York, Inc;

Director Springer-Verlag Japan; Director, Eastern Book Service, Inc., Japan; Senior Consultant, Academy for Educational Development; and Faculty Associate, Colorado State University.

Leland S. Prussia is the former Chairman of the Board of BankAmerica Corporation and Bank of America NT&SA. Prior to his appointment to Chairman, Dr. Prussia served as Executive Officer of the bank's World Banking Division. He retired from BankAmerica Corporation in 1987. Primarily involved in economic and financial consulting and advisory work since his retirement from the Bank of America, Dr. Prussia is a member of the Board of Directors and consultant to Far West Federal Bank of Portland, Oregon. He is also a member of the board of Sand County Ventures, Inc. of Palo Alto, California. Dr. Prussia serves as an Advisor to the Nippon Credit Bank of Tokyo, Japan and is a member of the board of Nippon Credit Trust Company of New York.

Jeanne Sullivan has been acknowledged internationally as a pioneer in the field of employee assistance/occupational alcoholism and chemical dependency treatment programming. In 1976, she founded the Industrial Alcoholism Institute in Chicago, Illinois. From 1978 to 1983, she chaired the Section on Substance Abuse Problems in Business and Industry of the International Council on Alcohol and Addictions, Lausanne. She also served as International Vice President of the U.S.-based Employee Assistance Professionals Association. In 1990, at the invitation of the newly elected Solidarity Government, she conducted alcoholism intervention workshops in Gdansk and Warsaw for Solidarity leadership. Mrs. Sullivan serves as Vice President, Travelers and Immigrants Aid of Illinois, and is active in the American Refugee Committee. A graduate of Radcliffe College, with graduate degrees in both social welfare and education, Mrs. Sullivan has taught as adjunct faculty at several Illinois universities, including the University of Chicago.

George Stranahan's current business interests include the Flying Dog Ranch in Woody Creek, Colorado; Geo Leisure, Inc.; and Lauretta's Inc. He graduated from the California Institute of Technology with a B.S. in Physics and received both his M.A. and Ph.D. in Physics from Carnegie-Mellon University. Upon graduation from Carnegie-Mellon, he joined Purdue University as a Research Associate and subsequently jointed the faculty of Michigan State University where he was Associate Professor from 1965 to 1972. Dr. Stranahan was a founder of the Aspen Center for Physics, served as President and Chairman of the Center from 1962 to 1972, and is currently a Vice President of the Center. His articles have appeared in such publications as the *Astrophysical Journal, Physical Review, Physical Review Letters, Engineering and Science* and *The Mountain Gazette*. His affiliations include: Honorary Trustee and Vice President, Aspen Center for Physics; President, Aspen Community School; President, Aspen Educational Research Foundation; and Roaring Fork Land Conservancy.

Staff News

Bruce R. Abell

Bruce Abell joins the SFI staff October 1 as Vice President of Finance and Operations. Bruce has worked for the past 30 years in areas of national science and technology policy, defense policy, industrial technology strategies, and science communications. One of his first responsibilities will be to select a replacement for **Marcella Austin**, Comptroller, who has left SFI to pursue other interests.

Kimberly Bodelson. Photo by Cary Herz © 1991.

Kimberly Bodelson recently joined the SFI staff as Executive Assistant. Her administrative background encompasses the areas of executive search and finance. Reporting to SFI President, Ed Knapp, and Executive Vice President, Mike Simmons, Kimberly performs a wide range of administrative duties for the Office of the President.

A new addition to the Development Office, **Barbara Hodges** serves as the Development Secretary, assisting Director of Development, Susan Wider. Prior to joining SFI, Barbara worked for six years as a legal secretary and receptionist in the Santa Fe office of an Albuquerque-based law firm.

We are currently interviewing for a new Computer Systems Manager to replace **Robin Justice** who recently left SFI.

Filling the new Research Secretary role, **Deborah Smith** brings to the SFI over nine years' administrative experience from Cray Research and Control Data Corporation. Working with Director of Programs, Ginger Richardson, and Program Coordinator, Andi Sutherland, Deborah provides administrative support for the research staff and oversees the SFI-wide database.

Joan Ulibarri is a welcome addition as the Publications Secretary. She assists Director of Publications, Ronda Butler-Villa, and Publications Assistant, Della Ulibarri, in all activities of the Publications Office, and will provide support for the Executive Editor of the journal *Complexity* in the near future. Prior to joining SFI, Joan served as a secretary in the Law Enforcement Division of the Department of Game and Fish.

Charley and **Della Ulibarri** were blessed with a son, Diego, on June 5, 1991.

Readership Survey

Please answer the following questions so that we can make the SFI Bulletin more valuable to you. Then cut along the dotted line, fold in thirds with our address showing, tape closed, and affix a stamp. Thank you for your time.

1 Please rate the Bulletin in terms of each of the following categories
(1=Poor; 2=Fair; 3=Satisfactory; 4=Excellent)

_____Quality/Readability of the Articles
_____Usefulness to your work
_____Diversity of content
_____Overall design

2 What topics are you particularly interested in having covered?

____
____
____
____

3 What features would you add to or delete from the SFI Bulletin?

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4 I consider the frequency of the Bullletin to be

_____Not frequent enough
_____Too frequent
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_____Save them for future reference
_____Pass them on to a colleague
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6 Which description(s) best decribes you?

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_____Research Scientist _____Other
_____SFI Donor

7 If you're a scientist, what is your field of expertise?

____
____

8 How did you come to currently receive the SFI Bulletin?

_____Participate(d) in SFI conference or research group
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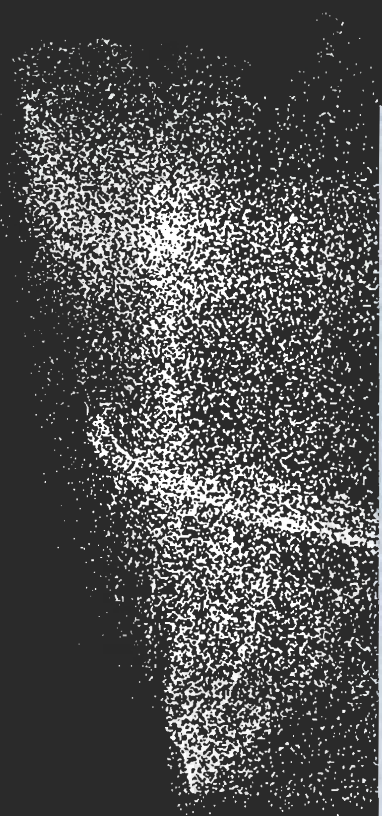
Time Series Prediction and Analysis Competition

August 1, 1991 – December 31, 1991

Organized by the Santa Fe Institute



A wide range of new techniques are now being applied to the time series analysis problems of predicting the future behavior of a system and deducing properties of the system that produced the time series. Such problems arise in most observational disciplines, including physics, biology, and economics; new tools, such as the use of connectionist models for forecasting, or the extraction of parameters of nonlinear systems with time-delay embedding, promise to provide results that are unobtainable with more traditional

errata, page 31

...Economist Buz Brock argued that we now had proof of significant nonlinearities in stock market patterns which could *not* have been recognized by conventional linear statistics. Physicists Doyne Farmer, Norm Packard, Richard Palmer, and Ed Jaynes, statistician *Steffan Lauritzen*, and computer scientist John Holland all expressed confidence that techniques such as local nonlinear estimation, genetic algorithms and neural networks, entropy maximization, and classifier systems would uncover patterns in the data, if there were any. ...

FOR MORE INFORMATION

Further questions about the competition should be directed to:

Time Series Competition
Santa Fe Institute
1660 Old Pecos Trail, Suite A
Santa Fe, NM 87501
tserver@sfi.santafe.edu

or one of the organizers:

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ADVISORY BOARD

dial-up: There are two dial-up lines: (505)988-1705 (2400 baud), and 505-986-0252 (any speed to 9600 baud). The settings for both lines are no parity, 8 bit words, 1 stop bit. At the connect press return; at the <cmd> prompt type `login tsguest` and `tsguest` for the password. At the next <cmd> prompt type `telnet sfi`, login as user `tsguest` (password `tsguest`) Using either kermit or xmodem, retrieve the file instructions. When you are finished, logout from sfi and from the <cmd> prompt.

mail server. Send email to tserver@sfi.santafe.edu with the phrase `send time series instructions` in either the subject or the body of the message. The mailer will return a file with more detailed instructions for requesting the data and submitting analyses.

pc disks: The data is available on disks in either IBM-PC or Mac formats. To cover the cost of distributing the data, send $25.00 to Time Series Competition Disks, The Santa Fe Institute, 1660 Old Pecos Trail, Suite A, Santa Fe, NM 87501, and specify the machine type, disk size, and disk density required. Instructions will be included with the disks on submitting a return disk with the analysis of the data.

Poster designed by R. K. Butler-Villa (SFI).
This data plot is a two-dimensional imbedding of coupled diode oscillators courtesy of Paul Linsay (MIT).

For further information write to: Time Series Competition, Santa Fe Institute, 1660 Old Pecos Trail, Suite A, Santa Fe, NM 87501 or send email to: tserver@ sfi.santafe.edu

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