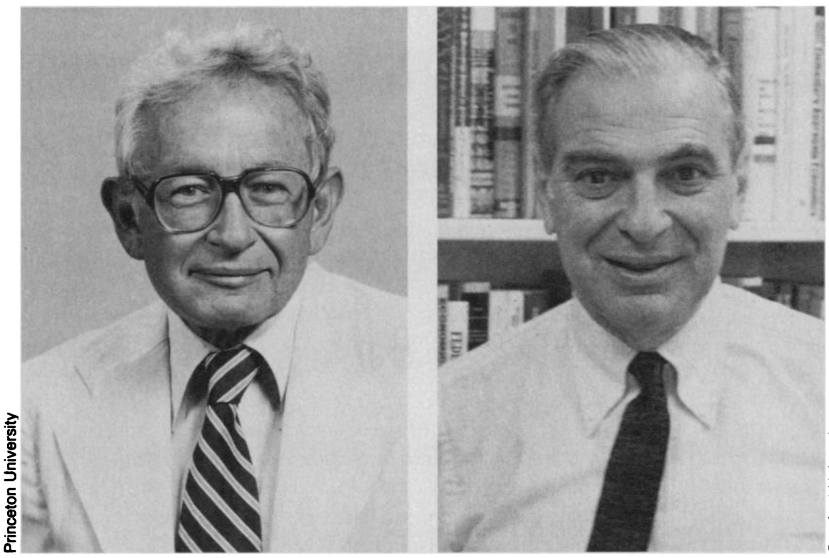
Strange Bedfellows

It is hard to think of a more unlikely collaboration than one between physicists and economists, but this is exactly what is going on at a former convent in Santa Fe, New Mexico

THEY MAKE AN ODD COUPLE, these two Nobel laureates. Philip Anderson is a condensed matter physicist who specializes in superconductivity; Kenneth Arrow is a theoretical economist who studies such things as how markets react to uncertainty. At first sight, you wouldn't expect them to have much in common, but you would be wrong.

Over the past 2 years, Anderson and Arrow have worked together in a venture that is one of the oddest couplings in the history of science—a marriage, or at least a serious affair, between economics and the physical sciences. If this unlikely liaison bears fruit, the result could be a hybrid theory that imparts to economics some of the tools and techniques developed for such fields as physics and biology.



Princeton University

Stanford University

Physicist and economist. *Anderson (left) and Arrow kicked off an unusual collaboration by inviting ten physical scientists and ten economists to meet in Santa Fe.*

"What we're trying to do," Anderson says, "is insert some new ideas into the foundations of economics that we [physical scientists] were shocked to find weren't there."

This ground-breaking venture is taking place under the auspices of the Santa Fe Institute, where economists and physical scientists—physicists, probability theorists, mathematicians, computer scientists, and at least one biologist—are meeting to exchange ideas and see what they can learn from each other. Anderson and the other scientists in the project think they have something to offer because, like economists, they deal with complex systems whose many parts interact nonlinearly. The economists are not quite so sanguine, but they are definitely interested in seeing what their counterparts can offer. "The occasional forays by physical scientists into economics have usually, but not always, been trivial," Arrow has been quoted as saying, but he has enough hope for this particular foray that he has lent both his time and his name to it.

Although the project may seem somewhat quixotic, its roots are deep in the practical soil of the business world. In 1986, John Reed, chairman of Citicorp, found himself dissatisfied with state-of-the-art economic forecasting because, among other things, it had allowed Citicorp to run up $15 billion in loans to Third World countries that looked as if they might never be repaid. Having a degree in metallurgical engineering himself, Reed looked to the physical sciences for help, and he asked the Santa Fe Institute to find ways to improve economic forecasting.

That call led to a meeting at the institute in September 1987 funded by Citicorp. Anderson, who was on the board of the institute, invited ten physical scientists, and Arrow, who was recruited by Anderson, invited ten economists. The two groups traded ideas on how to deal with complex economic systems. The gathering was successful enough to convince Citicorp to provide major funding for a continuing economics program at the institute, which now has anywhere from 8 to 15 researchers in residence at any given time, evenly divided between economists and physical scientists. They are mostly young but highly regarded in their fields and come from some of the best science and economics schools in the country—places such as Princeton, Caltech, Stanford, and Chicago.

As might be expected, the economists and scientists have found that things get rather interesting when two such different cultures collide.

Richard Palmer, a physicist at Duke University, recalls that first meeting in September 1987. "I used to think physicists were the most arrogant people in the world," he says. "The economists were, if anything, more arrogant." Both groups came into the meeting with skepticism and preconceived ideas, he recalls. The economists felt the physical scientists could not possibly help with their problems, and the physical scientists thought economics was a mess and there was not much you could do with it.

Brian Arthur, an economist from Stanford University who now serves as director of the institute's economics program, remembers that for the first 2 or 3 days there was "a lot of stepping around each other, looking each other over." Then the barriers broke down and the atmosphere was electric, he says, with people staying up until 2 or 3 in the morning.

"The chemistry was right," says physicist David Pines of the University of Illinois, who organized the meeting along with Anderson and Arrow. "The noneconomists were fascinated that the things they had been working on could be applied. Here was a whole new playground."

That sense of sport, with people knocking new ideas around like volleyballs, has persisted in the Santa Fe program, the researchers say. "There is a type of conceptual play I have rarely encountered," says biologist Stuart Kauffman of the University of Pennsylvania, who was at the meeting in 1987 and is now working half-time at the institute for 2 years. "Almost every day, I find myself

Santa Fe Institute

Fun time at the institute. *From left: Alan Perelson and David Campbell, Los Alamos National Laboratory; Richard Palmer, Duke University; Norman Packard, University of Illinois; and Marcus Feldman, Stanford.*

hearing ideas—not facts, but ideas—that I have never heard before. We're all hearing and borrowing from one another at a frantic rate."

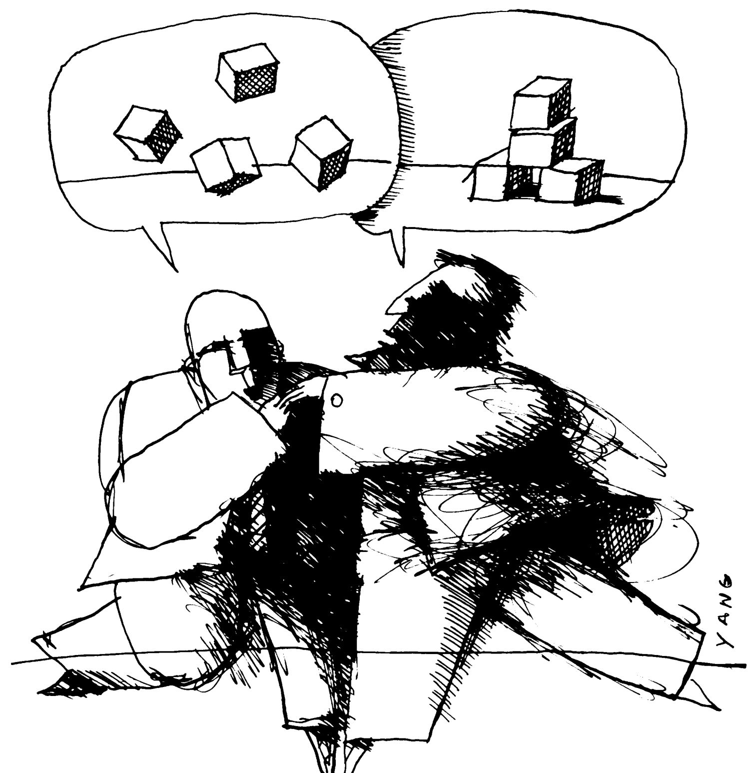
The participants must be "people who can live with a certain amount of conceptual chaos," Kauffman says. Many good scientists are not comfortable with the no-limits nature of the work that goes on there, he says, but for those who are, the experience is exhilarating.

How do two groups of people from such different fields as economics and physics learn to work together? "It's not as difficult as you might think, once you translate the language," Anderson says. However, once the translations were made, the two groups found that they approach their subjects in quite different ways.

The physical scientists were flabbergasted to discover how mathematically rigorous theoretical economists are. Physics is generally considered to be the most mathematical of all the sciences, but modern economics has it beat. Palmer, a condensed matter physicist, says economists use much more "fancy mathematics" and hard-to-understand notation than physicists. "You can't publish in economics journals without theorems," he adds. Anderson says one of the economists in the program "can't open his mouth without talking in terms of theorem-lemma-corollary."

The mathematical rigor of today's theoretical economics, Arthur explains, can be traced to the 1950s, when Arrow and Gerard Debreu founded a school of economics that worked explicitly from a set of axioms about the actions of economic agents—people, groups of people, businesses, or entire countries. "A whole generation of mathematical economists joined in a movement that believed in spelling out the assumptions that were being made," he says. "Now that's become the only way you can do economics, and physicists find that surprising."

The flip side of the physicists' surprise at the rigor of the economists was the economists' astonishment at the physicists' lack thereof. A short while ago, Arthur says, physicist Per Bak spoke at the institute about self-organized criticality, a concept used to explain scale-free behavior in complex physical systems (see box). It was all quite impressive, Arthur recalls, and at the end of the talk an economist stood up and asked Bak about his proofs. Bak replied that the results were all from experimental work done on a computer. "You can whip up theorems, but I leave that to the mathematicians," he said. Arthur comments: "The economists could not believe that that constituted research. We found it shocking that you could do science that way."



This difference in approach arises, Anderson says, from the difference in the amount of data available to the two fields. Because physicists have plenty of data, they can follow their noses with back-of-the-envelope calculations or computer simulations, secure in the knowledge that checking against experimental evidence will not allow them to wander too far off course. Economists, on the other hand, have very little hard data, so they must spell out their assumptions carefully and depend on rigor more than intuition.

A related difference between the disciplines is illustrated by a recent incident at the institute. A group including Arthur, Palmer, and Yale economist John Geanakoplos ran across a problem they could not solve immediately, and so they decided to do it as homework. That night, Palmer set up a computer program to approximate the answer, while Geanakoplos solved it exactly with pencil and paper. Comparing notes the next day, they found they had reached the same solution. It seems a small thing, Arthur says, but the economists in the group were taken aback by Palmer's computer short-cut—they would have never thought of it.

Lessons like this seem to be sinking in with many of the economists. "I have been using more numerical simulations in my work," says José Scheinkman, an economist at the University of Chicago. His time at the Santa Fe Insti-

Esoteric Borrowing from Physics

Even in the strange world of theoretical physics, spin glasses and self-organized criticality are rather esoteric creatures, but this doesn't bother the economists at the Santa Fe Institute. They'll try anything once.

The researchers at the institute began learning about spin glasses when it was suggested they might be good models for the behavior of complex economic systems. A spin glass, the economists discovered, is a complicated state of matter probably best understood in contrast with magnets. In magnetic materials, the individual atoms each have a spin, a quantum mechanical property that makes the atoms act like tiny magnets. In some materials, such as iron, the individual atoms are conformists—they tend to point their spins in the same direction as the spins on the neighboring atoms. Because of this, a piece of iron is in an optimal state when the spins of all the atoms are aligned. In other materials, the atoms are contrarians and align their spins to point in the opposite direction from their next-door neighbors.

A magnet would be a fine model for the economy if everyone did exactly what his neighbors did. However, except for a certain amount of keeping up with the Joneses, this is not the case. A spin glass is more like the real world, in the sense that in a spin glass some pairs of atoms want their spins pointing in the same direction, while others prefer their spins in opposite directions. Indeed, a single atom in a spin glass can be a conformist with respect to one of its neighbors and a contrarian with respect to another. It is as if Smith and Jones want to own the same model car, and Smith and Brown want to own the same model, but Jones and Brown want to have different models from each other. You cannot satisfy everyone. The resultant balancing of desires that goes on in a spin glass leads to very complicated solutions and seems analogous to what happens in an economy.

Although it now looks as if the mathematical techniques developed to analyze spin glasses have no immediate applications to economics, spin glasses do offer a powerful analogy for the real world, says Princeton's Philip Anderson. A spin glass can settle into a state that is a local but not a global optimum, he says. In such a local optimum, the material cannot move into a better—lower energy—state merely by switching one or a few spins. It would need to switch thousands or millions of spins simultaneously in order to move into a lower energy state, and such an event is very unlikely. Thus a spin glass can find itself stuck in a state that is less than optimal. In the same way, Anderson says, an economy might find itself in a configuration that is not the best possible but that is difficult to get out of. "We think the whole society can get itself stuck in a backwater with everyone doing the best he can within local parameters but the society as a whole not working very well," he says.

Several researchers at the institute also investigated the idea of self-organized criticality for possible insights into how economies behave. Per Bak, a physicist at Brookhaven National Laboratory, originally developed the idea to explain how physical systems can have similar types of behavior occurring at many different length scales. The standard example of self-organized criticality is the pile of sand in an hourglass. When one more grain of sand is added to the pile, several things can happen: The extra grain might knock one or a few grains out of place; it might set off a stream of sand going down one side of the pile; or it can start a big avalanche. This unstable situation where adding one more grain of sand can trigger avalanches of different, unpredictable sizes is called a critical state. The criticality is self-organized in the sense that the pile of sand naturally organizes itself in this way.

Bak uses self-organized criticality to try to explain scale-free behavior that appears in a number of physical systems. Might it not also occur in economic systems? Crashes in the stock market, for example, might be explained by the market reaching a critical state where it could drop by 5, 50, or 500 points.

Michele Boldrin of the University of California at Los Angeles has looked for self-organized critical behavior in certain economic models, and has found that with the proper choice of parameters he can design a system that evolves into a critical state. However, with more reasonable parameter values, he says, the agents in the system organize themselves into local communities, which prevents the entire system from being affected by a small stimulus—a single grain will not set off a large avalanche. He has not tested models of the stock market, but he says, "My initial intuition is that the stock market does not necessarily exhibit self-organized criticality." ■ **R.P.**

tute has made him more comfortable with using a computer to find an answer before trying to prove it rigorously, he says. Arthur says he too is learning to use computer modeling. "Before, most of my work was pencil and paper. Now it's pencil and paper and computer."

Despite their differences in approach, the economists and scientists have collaborated on projects in a number of areas, usually in teams of two, three, or four. Two areas that have received a great deal of attention are the specific question of how economic agents take the future into account when making decisions and the more general theme of how to model a system as complicated as a nation's economy.

A fundamental difference between the physical sciences and economics is that in economics the agents are conscious. People and corporations, unlike protons and proteins, determine their actions according to what they expect to happen in the future. The question of how this should be incorporated into an economic model faces everyone trying to understand the economy.

The Arrow-Debreu model handles the problem by assuming that economic agents make perfectly rational predictions about the future and then act according to what will maximize their returns. This axiom of "rational expectations" seemed patently untrue to the physical scientists, who are acutely aware of the difficulties of predicting the future. If meteorologists with powerful computers cannot predict the weather more than a few days in advance, how can John Q. Economic Agent predict accurately what the economy will do next year?

The rational expectations hypothesis is a cornerstone of the Arrow-Debreu approach, which is the reigning paradigm in economics today, and the axiom has proved its value by giving some surprisingly good predictions, Arrow says. Yet, he admits, the assumption can lead to some silly conclusions as well. "It generated a lot of useful work to have a model to attack or defend," Arrow says, but now he hopes to be able to develop a more realistic model.

The problem in developing a more realistic model is that if economic agents are assumed to be able to anticipate the future, but not perfectly—economists call this "bounded rationality"—then it is hard to know just how imperfect the rationality should be. "There is only one way of being right, but there are thousands of ways of being wrong," says Chicago's Scheinkman. How do you set the rationality dial?

This question set off some of the most provocative work to come out of the program, and it may turn out to be one area where the physical scientists make a significant contribution to economics. Arrow says that one of the most promising approaches to bounded rationality is one devised by John Holland, a computer scientist at the University of Michigan. Holland uses what he calls "genetic algorithms" to model how people make decisions. A genetic algorithm is a set of computer rules (for playing a game, for example) that modifies itself with experience. It improves its decision-making ability as it goes along, in other words. But in a complicated game, such as chess or playing the stock market, it will never learn to make perfect decisions. One way to set the rationality dial, Holland suggests, is to put the needle at zero initially and let a genetic algorithm decide how far up the dial it goes.

Holland and Brian Arthur are applying this approach to see if they can explain complex behavior in the stock market. They are setting up a simple stock market peopled by computer automata. Initially, the automata are provided with simple rules for buying and selling, but as they go along they develop new, more effective rules—they learn, just as real agents do. The computer scientist and the economist hope to find that their artificial market develops a complicated psychology of its own, perhaps exhibiting such things as speculative bubbles and crashes.

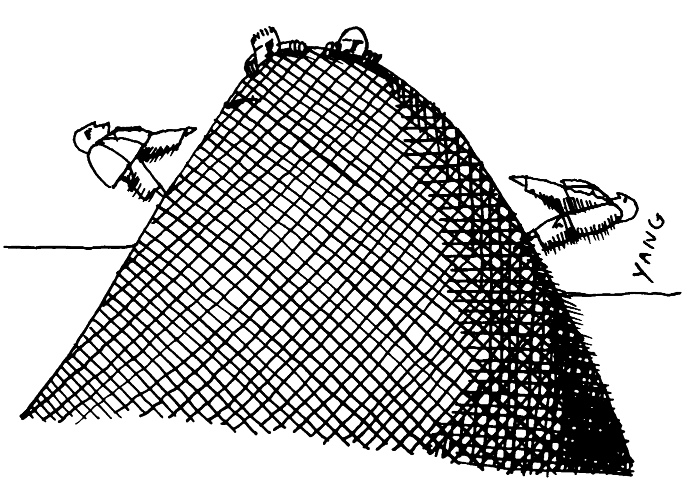
The more general question of how to model a complicated economic system has generated several different efforts. One was an attempt to see if the tools developed to analyze spin glasses—a concept from condensed matter physics—have any application in economics (see box). A second grew out of the concept of "rugged landscapes," an idea from evolutionary biology.

In thinking about the evolution of a species, biologists picture the space of all possible characteristics for a species in terms of a landscape of hills and valleys. A species that evolves more favorable characteristics is pictured as going uphill, while going downhill means the species is becoming less fit. If the landscape is rugged—it has many hills—then the species may run into trouble on its evolutionary path. It might reach the top of a given hill, meaning that it cannot improve its fitness by any small steps, but other hills may be higher than the one it is on. Unfortunately, to get to the higher hills—to become more fit—it must first climb down into the intervening valleys and become less fit.

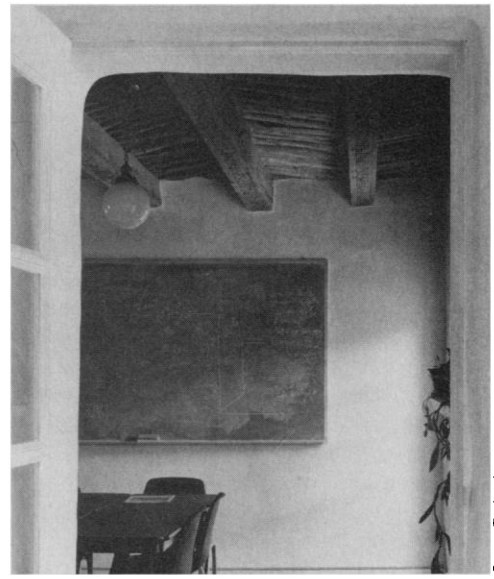
Kauffman says the models become very complicated, especially when several species are included. Consider what happens as two species, say a frog and a fly, coevolve. When the frog makes a move in its landscape—that is, it evolves some new characteristic—this changes the fitness landscape of the fly. "Now you're into game theory," he says, because the moves of one player are affecting the strategy of the other. Kauffman has analyzed some simple ecologies using this approach and found that with just two species, each may get stuck on top of hills—neither can make a move without decreasing its own fitness. The two-species system is at an evolutionary dead end. However, with a larger number of species in the ecology, he says, although small subsets of them can get stuck, others keep changing.

Do these ideas have implications for economics and the way different economies coevolve? Kauffman says there are many parallels between an ecology and an economy, suggesting that ecological models may capture many aspects of an economy. However, because economic agents have foresight, the ecological models cannot be applied directly.

Both physicists and economists have also used hill-climbing analogies in their own work. In economics, the basic question is which direction an economy should go in order to improve. Normally, Arrow says, economists have worked with models that have only one hill, so that the problem was only how to get up that hill; there was no worry about whether an economy might get stuck on a low-lying hill. "I don't think we [economists] recognized the depth of our problem until we talked to the physicists," he says.



These questions illustrate a basic theme


Santa Fe Institute

An odd juxtaposition. *Rooms at the Santa Fe Institute, a former convent, have old wooden ceilings and new blackboards with mathematical equations.*

at the institute. Arthur says he sees a "Santa Fe approach" emerging that views the economy as a complex, constantly evolving system in which learning and adaptation play a major role. Eventually, he says, this could expand the current view, much influenced by classical physics, that depicts the world as relatively simple, predictable, and tending to equilibrium solutions. "We have high ambitions," he says, but he cautions, "I don't want to say we're going to change the world."

As a rule, the physical scientists seem more optimistic than the economists about what the collaboration will produce. Kauffman, for instance, says, "I'm fairly convinced that the things coming out of here will be considered seminal in 10 years."

Meanwhile, look for other surprising juxtapositions from Santa Fe. The privately funded institute, which is working out of a former convent until it can find the money to build its own facilities, is slowly building a reputation for its work in various areas, all related to the general theme of complex systems.

Pines, who serves as cochairman of the institute's science board, says its goal is nothing less than "to define the scientific agenda for the next century." One way it plans to do this, he says, is by breaking the barriers between various disciplines.

Last November, for instance, the institute brought together a collection of physical and social scientists for a workshop on international politics and global security. "Global security is too important to be left to the politicians," Pines says, "just as economics is too important to be left to the classical economists." ■ **ROBERT POOL**