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Between Chaos and Order:

What Complexity Theory Can Teach Business

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By David Berreby

The problem: after truck bodies trundle off the assembly line at the General Motors Corporation plant in Fort Wayne, Ind., how do you get them painted with the least expenditure of material and time?

The standard approach, applied at plants all over the world, is a plan that routes each truck to a line in front of numerous tunnel-like passages, where spray guns cover it with coats of paint. A centralized controller keeps track of where every truck is going and coordinates the routing with the use of different colors by each paint station. The highly interconnected system works fine as long as nothing goes wrong; but once any part of it stumbles, it throws off the workings of everything else.

In Fort Wayne, though, there is no such plan and no such risk--thanks to a developing school of thought about how organizations work that has broad implications for companies and their managers.

Each of the 10 paint modules in the G.M. plant is operated, instead, as a free agent by a computer whose program has a simple goal: paint as many trucks as possible, and use as little paint as possible. Without regard for what any of the other paint booths are doing, or what else is happening in the plant, each booth makes an electronic "bid" for each truck, and the job always goes to the lowest bidder.

If the line in front of a booth is long, it bids zero--signaling that it is not trying for more work. If it has capacity, it bids either high or low, depending on how much capacity. In a microsecond, all the bids are in and the modules' computers, akin to players in a poker game, compare them and assign the truck to the "winner." In the case of a tie, the nearest low bidder gets the job. The game even extends inside the modules, to the operation of the computer-controlled spray guns.

Like a market sorting supply and demand through the actions of individual traders, the system of self-interested modules quickly evolved a pattern for painting trucks that saves G.M. $1.5 million a year over the standard approach, according to Howell Mitchell, an engineer at Flavors Technology, the New Hampshire consulting firm that designed the system. And if G.M. institutes major changes in the way the assembly line produces truck bodies, or changes the ratio of black trucks to white, no planner need go back to the drawing board to redesign the painting operation. The modules, each one still trying to maximize its success, will collectively evolve the best new pattern on their own, says Richard E. Morley, Flavors's president, who conceived the system. On line in Fort Wayne since 1990, the system is being considered by G.M. and other auto makers for a number of other plants.

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Illustration by Doug Bowles

Mr. Morley's approach is a sign that practical applications of complexity theory, a way of thinking once confined to science and mathematics, are starting to make headway in business and finance. The approach emphasizes the ways in which a factory or a company resembles an ecosystem or a market, evincing patterns as it grows, rather than a machine whose parts and functions have been planned out in advance.

The physicists, mathematicians, biologists and computer scientists who work on complexity theory have been emphasizing for years that complex systems seem to organize themselves. Under the rubric of "chaos theory," their ideas have captured imaginations in fields as far apart as literary criticism and radio astronomy. Meanwhile, as Sherry Turkle, a professor of the sociology of science at the Massachusetts Institute of Technology, points out in her new book, "Life on the Screen," computers have helped persuade millions of Americans that knowing the parts of a system won't make you able to foresee all the complexity that can arise as its hardware and software interact.

With an impetus from chaos theory and from computer culture, then, complexity theory is beginning to find its way onto the factory floor and into the executive suite.

Indeed, says Stuart Kauffman, one of the leading thinkers in the field, complexity theory promises to clarify the work not only of evolutionary biologists and physicists, but also of plant managers and economists. Over time, it will allow both the practitioners and the theoreticians of the business world to rewrite their playbooks, says Mr. Kauffman, author of the complexity field's new bible, "At Home in the Universe: The Search for the Laws of Self-Organization and Complexity."

The ramifications are enormous, adds Chris Meyer, a partner at Ernst & Young who heads the firm's Center for Business Innovation. "This work is pointing the way toward how we'll think about managing organizations in the future," he says. If the complexity theorists are right, Mr. Meyer continues, then the current modus operandi of most businesses--make accurate predictions about a few key variables, and keep control over them--is a grotesque oversimplification, like representing a mountain as a mathematical pyramid.

"Suppose you come down from Mars and you see taxicabs working the streets of New York," he says. "You want to simulate that. You might think, well, there's probably a big dispatcher in the sky sending all these cabs where they need to be. That's what people are trying to do when they use M.R.P.--manufacturing resource planning."

Complexity theory offers a very different approach, leading to a very different simulation, Mr. Meyer says. "Each yellow car has a simple brain following a few simple rules: Stop for anything that waves. Go where it says." That simulation, he says, would give you reality--all these cabs moving about, coalescing and separating in complicated patterns. "That simulation is going to be robust and simple and it's going to account for the diversity you actually see."

Mr. Kauffman and other complexity thinkers would argue that all those cars doing their own thing would naturally evolve the most efficient distribution of vehicles for the purpose--a solution likely to be better than anything a planner could come up with.

Mr. Meyer concurs. "M.R.P. and strategic planning are a disaster," he says. "This is not what people really do." Simulations from complexity theory have the great merit of feeling like real organizations with real people in them, he says. That's one clue that they are on the right track. After all, the universe is full of markets, ecosystems, solar systems, brains and other complex wholes that seem somehow more than the sum of their parts--and rather than being designed, they assembled themselves.

It was the study of such systems that gave rise to chaos theory and made James Gleick's "Chaos" a best seller in 1987, popularizing complexity theory's ideas. For example, there is the butterfly effect (in a complex system, causes are not proportional to effects, so that, to use a metaphor so famous it is now a cliché, a butterfly flapping its wings in China can cause a blizzard in Chicago). Another important concept is that most of life is nonlinear. A nonlinear system is any collection of things that, thanks to the butterfly effect, cannot be represented by linear equations, where twice as much cause yields twice as much effect.

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Illustration by Doug Bowles

Chaos theory represented a bold effort to portray a nonlinear world more accurately, and to tease more information out of situations that seem completely unpredictable, like the jiggles of a stock market. (See accompanying article.)

In the last few years, though, those who work on complexity theory--especially at the field's mecca, the Santa Fe Institute in New Mexico--have claimed to see not only the laws of chaos, but also those of order: A powerful explanation for how any collection of components, be it a cell, a person or a corporation, will organize itself.

The premise of complexity theory is that such organization is not a lucky accident, but the result of laws of nature that we don't yet fully understand. Once we do, argues Mr. Kauffman, a biologist and medical doctor who is one of the intellectual stars at the Santa Fe Institute, we will see that complex systems, left to their own devices, don't fly apart into chaos. In the nature of organization itself, he says, there is "order for free."

Moreover, the evidence from his work suggests that these laws actually impel complex systems to the best possible solutions to their problems--a kind of creative window between the "leftist Italian" state of constant chaos and the "Stalinist" state of too much predictability and order.

"Life exists at the edge of chaos," Mr. Kauffman writes. "I suspect that the fate of all complex adapting systems in the biosphere--from single cells to economies--is to evolve to a natural state between order and chaos, a grand compromise between structure and surprise."

Sound like a day at the office? The implications of these ideas for management have long interested people concerned with organizations and economic systems. John S. Reed, the chairman of Citicorp, visited Santa Fe in 1986 and has been a strong supporter of the institute. So has Kenneth Arrow, the Nobel Prize-winning economist from Stanford. Two of complexity theory's leading lights--J. Doyne Farmer and Norman Packard--have left academia to apply their work to guiding investments for banks and corporations.

There are other signs of complexity's growing allure. The Santa Fe Institute's Praxis Group, a floating seminar on applying complexity theory to business and other organizations, held well-attended sessions last summer in San Francisco and London (at $3,000 and £2,500 a head, respectively) for managers from both the private and public sectors. Mr. Meyer has done his part, buying 1,500 copies of Mr. Kauffman's book to give to clients.

Still, applied complexity theory will not go down smoothly in most executive offices. After all, it posits a very different world from the one managers are trained to prepare for.

Consider a Kauffman hypothetical involving the BellSouth Corporation. "BellSouth needs to decide whether to invest billions in fiber-optic technologies," Mr. Kauffman writes. "Should BellSouth do so? What if, in two years, some bright kid thinks up a way to toss tin cans into the sky held up by fans placed at strategic intervals in such a way that fiber optics is less useful? Billions down the tube. Can BellSouth management be sure of what to do, given the unfolding technological frontier? No."

So what CAN you do? Stop trying to control a complex system from above. Remember the butterfly effect. Instead, watch for the "emergent properties" that arise as a system organizes itself and devote yourself to preserving the conditions in which the best solutions evolve.

Each actor in a complex system is trying to balance conflicting constraints, according to Mr. Kauffman. "Heavier bones are stronger, but may make agile flight harder to achieve," he writes. "Heavier beams are stronger, but may make agile fighter aircraft harder to achieve as well. Conflicting design criteria, in organism or artifact, create extremely difficult 'optimization' problems--juggling acts in which the aim is to find the best array of compromises."

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One way of mapping that struggle, developed by evolutionary biologists in the 1930's, is to imagine the environment as "an adaptive landscape whose peaks represent the highly fit forms," Mr. Kauffman writes. He has simulated many such landscapes on computers.

Everyone tries to climb to the peak of fitness and avoid the troughs, but of course what "fitness" is will change over time, and one of the most important factors changing the definition is what every other actor is up to. The departure of I.B.M. from the laptop business would make a great deal of difference to Compaq's fitness landscape, for example.

So like a slick on a roiling sea, the fitness landscape is constantly "deforming," rearranging its peaks and troughs as time passes.

"We are all, cells and C.E.O.'s, rather blindly climbing deforming fitness landscapes," Mr. Kauffman writes. "If fitness peaks are moving," he adds in a telephone conversation, "you want to optimally slide along as the world changes. If it's not changing too vigorously, you start to have a constant sweet spot emerging on the landscape."

Sometimes, Mr. Kauffman argues, the result of all this uncontrolled effort by all these actors is to evolve into a very stable and orderly regime--but interestingly, these predictable and solid arrangements tend to freeze everyone into positions that are merely O.K. No player in the ecosystem approaches its potential peak success. Mr. Kauffman calls such overly orderly arrangements "the Stalinist limit."

Another outcome that crops up in simulations occurs when everyone's pursuit of his own peak causes the system to never settle down to any kind of predictability--"the leftist Italian limit."

Consider that very complex adaptive system, the aircraft carrier. "What does the captain do? The first time he says, 'Man the battle stations,' there's confusion and people going the wrong way and maybe an airplane falls over the side," Mr. Kauffman says. "Then people talk to each other, and it turns out that if this team runs that way instead of this way, you can keep the plane on the deck next time. But maybe that makes trouble on another deck. And so the different teams on the carrier coevolve to the point where when the captain says, 'Man the battle stations,' everything gets done fast. That's not different from a whole bunch of species deforming each other's landscapes."

Insights into how this works, Mr. Kauffman writes, are likely to come from the concept of "self-organized criticality," which emerged from studies of sandpiles by the physicists Per Bak, Chao Tang and Kurt Wiesenfeld. They added sand at a constant, slow rate. Once the pile got high enough and its slope steep enough, avalanches started--a lot of small ones and a few large ones. Plotting size and frequency of avalanches produced a curve, which in turn yielded a power law.

In other words, Mr. Kauffman writes, "the system tunes itself, as if by an invisible hand, to the critical-rest angle of sand and remains poised there." Though it isn't immune to immense and sudden change, such a system teeters along most of the time and displays a high degree of organization. And, oddly enough, it is in this realm where the most climbers get closest to their peaks--successful adaptations in evolutionary terms, low-cost products in industrial ones.

The hint of universal law in these simulations, Mr. Kauffman says, suggests ways that corporate strategists should look at organizational, technical and industrial problems. He believes it may be possible, using models developed for evolution, to find a signal of corporate success--a pattern indicating that an organization is in the "sweet spot" between rigidity and chaos. "Perhaps this could be one of the first intellectual foundations for organizational flattening," he says.

According to his simulations, the optimum solution to the problem of making a living emerges in a system full of autonomous actors all trying their best to get by. It follows then that the best way to meet some corporate goal would be to divide the problem into "patches," and put each patch to work solving its particular piece of the puzzle. "If the entire conflict-laden task is broken into the properly chosen patches, the coevolving system lies at a phase transition between order and chaos and rapidly produces very good solutions," Mr. Kauffman writes. "Patches, in short, may be a fundamental process we have evolved in our social systems, and perhaps elsewhere, to solve very hard problems."

They may even provide a theoretical underpinning for our faith in democracy, he argues. The United States, after all, is broken into patches called states. And these are broken into smaller patches still.

Now, this makes paying obeisance to complexity theory seem almost a patriotic duty. Still, you could object that these simulations merely put new terms to a process that is obvious enough--for example, breaking down the creation of a supersonic transport into an airfoil team, a seating team, a hydraulics group and so on.

But what the patches model can offer is a new way to think about things when they go wrong, says Mr. Meyer of Ernst & Young. For example, if no solution to the supersonic plane design is coming out of all those different units, perhaps the problem is that the process has been broken down into too many patches, creating chaos. Or too few, creating the insufficiently free Stalinist limit.

Certainly, when Mr. Kauffman simulates patch creation on his computers, that is what happens unless the patches are the right size. "You could build a computer model of your plant," he says. "Inevitably, you misspecify where the patches should be divided. With a model, you can try different ways of patching up the problem--keep playing with them on the computer, and find which way does best."

A similar concept to patches is "receiver-based communication," in which pilots, for instance, coordinate with one another as they fly together, rather than getting directions from ground control. Simplified simulations of such individual actors show that the best overall result happens when each one ignores its neighbors some of the time. So "in hard conflict-laden problems, the best solutions may be found if, in some way, different subsets of the constraints are ignored at different moments," Mr. Kauffman writes.

All these properties emerging naturally out of computers, though, do seem to beg the question of what a manager can do. If it all happens naturally, why go to work? How do you fight the 21st century equivalent of the law of gravity?

"Sure, there are many states where the manager is helpless," Mr. Meyer says. "Even Pat Riley says so."

Mr. Kauffman agrees, adding, however, that managing the interplay of accident and law may be what managers should do--and do do, in the best of circumstances. Consider that aircraft carrier, he says. "After that first shakedown cruise, where the planes fell off the deck and they figured out how to get better at manning the battle stations, what has the captain done? Has he managed each event? No. We're looking at a process of coevolution. Perhaps the captain's job is knowing how and where to push to keep the system in the window--neither rigidly ordered and thus inefficient, nor completely chaotic."

Mr. Meyer illustrates the point with a computer simulation called George's Party: "The noise level at a cocktail party is an emergent property. We have three levels in the simulation--convivial chat, a raucous roar and dancing debauchery. Each individual has two rules he or she is trying to follow: 1. Talk loud enough to be heard and 2. Stand close. As your guests arrive, you get this murmur. Then you get to a critical point in the noise and everyone decides to speak louder and you settle into another, louder state. It's worth your while to see if there are things you can do to kick the party up into the louder state. One thing you can do, for instance, is turn on the stereo. Once you get there, you can turn the stereo off and everyone will keep on talking loud.

"So 'George's Party' is a model of managerial intervention. In the party, maybe 40 guests will make a raucous roar no matter what. But knowing what you can do to raise the noise when you have only 15 guests makes you a better host."

George's Party has other lessons to offer. "It can also be useful in learning to manage innovation," Mr. Meyer says. "For instance, in the portfolio model of strategy, market share is stable, and maintaining it means low costs. Now you come to a period of explosive growth. You could say that the prescription about focusing your energy on market share won't work, because you need to be scattering lots of seeds. You don't know which one will be selected and amplified. So what you manage is your portfolio of capabilities, not markets. So if you're Sony, you worry about mastering miniaturization, wherever you might need to, rather than about keeping your share of the market for Walkmans."

Certainly the idea that vastly complex things like cells and people and nation-states arise out of the interaction of a few simple rules is appealingly grand. And for the last 300 years, when scientists have said there is a deep unity underlying supposedly disparate phenomena, following them has proved a good bet. In all-encompassing laws there is beauty, excitement, a gee-whiz amazement. Perhaps we have a temperamental fondness for the idea that a few principles underly all our perplexities and mysteries and all their details. After all, people don't buy books called "7,000 Habits That 23,401 Highly Effective People Have." Managers, like scientists, like the all-encompassing principle.

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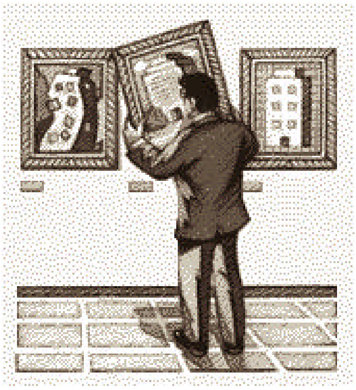

Illustration by Doug Bowles

Sure, writes Mr. Kauffman in his new book, we can't understand every detail of evolution, every reason behind every part of every species. Remember the butterfly effect. "We must instead simply stand back and watch the pageant," he advises. Beneath the details, he writes, can be "deep and beautiful laws governing that unpredictable flow." Many "features of organisms and their evolution are profoundly robust and insensitive to details," he argues.

Maybe so, but in science, as in management, there is always a rival strain. Some people delight in detail. They will fight generalization as an effort to throw the baby out with the bathwater. A law broad enough to explain sandpiles and corporations and starfish, they will argue, will have the sandiness and corporate culture and starfishiness (Abstract)ed out of it, so that it says nothing important. One of the most extreme examples of this kind of scientific mind was probably Dr. Alfred Kinsey, who was a student of wasps before he turned to human sexuality. Asked what he could say about the wasp in general, after decades in which he had examined hundreds of thousands of different insects, he replied that he hadn't yet seen enough specimens to generalize.

The detail people are not always wrong. As with all intellectually alluring fads, complexity theory is in for a backlash, and it may have already started.

In its June 1995 issue, for instance, Scientific American asked, "Is Complexity a Sham?" Building on a paper published in Science in 1994, Scientific American's veteran writer John Horgan argued that the main tool used by complexologists--the computer simulation--is an inherently flawed method for understanding the world.

The paper, by the philosopher Naomi Oreskes and two colleagues, argues that because our knowledge of "real world" phenomena will always be partial, we can never verify with certainty that a computer model represents the world. Mr. Horgan, noting that some scientists have given up on the chaos and complexity hype, argues that complexity may join catastrophe theory, cybernetics and information theory on the ash-heap of ideas that, whatever their utility in their own spheres, were once touted as all-powerful explanations.

Not entirely convinced, but interested, a number of the leading research consulting firms are looking into complexity's possibilities.

Mr. Kauffman himself acknowledges the skeptics. "The consulting community is filled with fad after fad," he says. "You have to use caution, because this is a new science. Whenever humanity invents a new widget, we try to apply it to everything. Then things settle down and it gets used for what it's appropriate for. They tried foxglove as a cure for everything before they settled down to using digitalis for heart disease."

But whatever complexity's long-term legacy turns out to be, the skeptics have some explaining of their own to do if they mean to turn the tide of opinion this early in the game. Just what do they make of the success of the hardworking paint booths of Fort Wayne, Ind.?

PREDICTING A MARKET

J. Doyne Farmer, one of the principals in the Prediction Company in Santa Fe, N.M., often shows an odd looking photograph with his charts and diagrams when he gives a lecture.

It looks like the cross section of a long seashell, but it's actually the meeting of a stream of liquid nitrogen with another made of helium and argon--"a very turbulent fluid flow," Mr. Farmer says. "Until this picture was taken at Cal Tech in 1972, people believed turbulent fluid flows were totally random. But look at it."

For Mr. Farmer and his partners and employees, the point is not rhetorical. The Prediction Company survives by calling ups and downs in the market--using complexity theory techniques to elucidate the supposedly "random walk" ups and downs of commodity and currency markets. Since 1991, the company has guided investments for a number of banks and corporations, beginning with the Swiss Bancorp. Mr. Farmer and his partners decline to reveal the size of their portfolio or to provide exact numbers on how it has fared, but say they are comfortably ahead of the broad market performance.

The company's method is as basic in principle as the Cartesian graph, with its X and Y axes. It begins with measurements--hard numbers that describe the "state" of a complex system at any one moment (what those numbers represent, be it populations of elk or prices of stock, doesn't make any difference).

For each instant in time, the different measurements are treated as coordinates for a single point on a graph. For example, Mr. Farmer explains, a clock pendulum could be described at any single instant by two measurements--say, the speed with which the pendulum is moving toward the right, and its position relative to its natural resting place in the center.

By the next measurement, of course, time has passed and the position and velocity have changed, so the next point will be elsewhere in this imaginary realm, which Mr. Farmer and his partner Norman Packard call "state space." Linked together, a lot of these imaginary points can form a shape or pattern. If a computer were mapping the pendulum's swings, inserting each new coordinate as soon as the measurements were taken, its screen would soon show a neat spiral taking shape on the graph, with 0,0 at its center.

Because the 0,0 point seems to pull the other points toward it, it is called an "attractor." The simplicity of the spiral pattern suggests that a very simple rule governs the swing of the pendulum. So the computer, by projecting the state-space spiral a little bit, would be able to predict where the pendulum would be a few moments in the future.

It is this type of state space that the Prediction Company's network of computers creates for its market tracking, using for coordinates the prices of stocks, commodities and currencies and the movements of various market surrogates, like the Standard & Poor's 500 Index, which tracks the performance of 500 widely held common stocks (the data all come zooming in over superfast modems).

But the Prediction Company's state-space maps involve not two variables, but hundreds. Naturally, each extra variable means adding another axis to the graph, increasing its dimensions (state space being imaginary, there is no limit to the number of dimensions a map can occupy).

On the other hand, there is a practical upper limit to how many dimensions state space can have if it is to be of any use in forecasting. Even if a computer could cope with the 500,000-dimension state space that would result from 500,000 variables, there would be the problem of getting enough data. Each additional variable (or "degree of freedom," in chaos-talk) involves a vast increase in the amount of information that has to be crunched.

"By the time you get to a seven-dimensional space, you'd need millions, if not billions, of data points," says Blake LeBaron, an economics professor at the University of Wisconsin who has worked with chaos techniques for years.

To serve as a tool for prediction, a state space need not be as simple as the pendulum graph, but it does need to have a low dimension.

The state space that describes markets, Mr. Farmer says, "is not very low-dimensional, and, therefore, not very predictable." In fact, he says, "the only thing worse than financial data are things relating to radioactive decay or quantum mechanics." A really good understanding of the chaos of markets, he says, is years away.

In the meantime, the company's computers, Mr. Packard says, "look at a space of possible dimensions in the hundreds," trying to find the "pockets of predictability" where, for reasons that remain "a subject for future research," a state-space map of only a handful of dimensions is suddenly sufficient to predict what will happen next.

Occasionally predicting what will happen 5 percent of the time doesn't sound like much, Mr. Farmer says, but remember that most of the other players behave as if the up-and-down dance of prices is random.

"If you look at the statistics on money managers, the majority of them perform roughly equivalent to a coin toss--straight 50-50," he says. "So even if we're wrong 45 percent of the time, we're still doing much better. There doesn't have to be much low dimensionality there for us to get extraordinarily rich."

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THE THEORY IN CONTEXT

Every few decades, a theory comes out of social or physical science that overthrows older notions that the world is under control.

In the 1920's, popular culture took up Freud's suggestion that we didn't have nearly as much of a grip on our psyches as we thought. In the 1970's, a number of popular books stressed that under the rules of quantum mechanics, knowing everything we want about any given subatomic particle is impossible. Both of those theories had captured the imagination of artists and intellectuals before making their way into the mainstream.

Now complexity theory--which suggests that organizations have to have an element of chaos to thrive--is taking its turn in the popular imagination.

"Linear" in office jargon is now practically a synonym for "old-fashioned," if not "bad." Moviegoers not distracted by T. Rex in "Jurassic Park" a couple of summers back could have heard Jeff Goldblum explaining chaos theory, which was complexity's first successful branch. And Tom Stoppard's play "Arcadia," which opened to adoring reviews in London in 1994 and later in New York, is, among other things, a remarkably lucid explanation of what the excitement is about.

To get more of a sense of the science out of which complexity theory evolved--and its potential for the business world--there is an abundance of books to consult, a number of them quite good. A few of the most complete:

"At Home in the Universe: The Search for the Laws of Self-Organization and Complexity," by Stuart Kauffman (Oxford University Press, 321 pages, $25, 1995).

"The Quark and the Jaguar," by Murray Gell-Mann (W.H. Freeman & Company, 392 pages, $23.95, 1994)

"Complexification: Explaining a Paradoxical World Through the Science of Surprise," by John Casti (HarperCollins, 320 pages, $25, 1994)

"Complexity: Life at the Edge of Chaos," by Roger Lewin (Macmillan, 208 pages, $10, 1992)