Chaos Theory: How Big an Advance?

To some, it's a novel intellectual weapon that can be applied in almost every field; but to others, it's nothing less than "Gödel's child": a window into the unknown

This is the last in a six-part series that examines how scientists in a host of fields are using chaos theory to study complex phenomena. The five previous pieces, which appeared between 6 January and 10 March, reported on chaos studies in epidemiology, population biology, physiology, quantum physics, and meteorology. This article explores whether chaos is merely an interesting idea enjoying a faddish vogue or is actually, as some of its proponents claim, a revolution in scientific thought.

IN POLITICS IT'S CALLED A REVOLUTION; in business, a hostile takeover. Scientists use a gentler term—paradigm shift—but the sense of sudden, radical change remains.

Some say science is in the midst of such an upheaval now. Scientific rebels marching under the banner of chaos are out to remake the world. Their goal: to replace the orderly universe of Newton and Einstein with a less predictable cosmos. Already they have won a few skirmishes, and their ideas have a powerful appeal that is attracting more followers all the time.

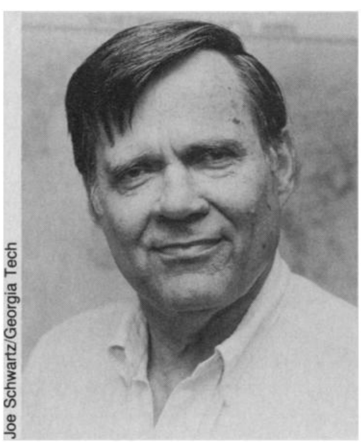
Yet the outcome is still undecided, and the ultimate relevance and importance of chaos theory to the real world are still unclear. When the smoke clears, will scientific history have been made, or will this all be relegated to the footnotes?

Joseph Ford has no doubts. "We are in the beginning of a major revolution," he says. "The whole way we see nature will be changed." Ford, a physicist at Georgia Tech, has been working in the field since the late 1950s, long before it had a catchy name and a high profile. His interest was piqued, he says, by one of the long-standing questions of statistical mechanics: Where does the randomness necessary for statistical behavior come from if the universe is at heart an orderly, deterministic place?

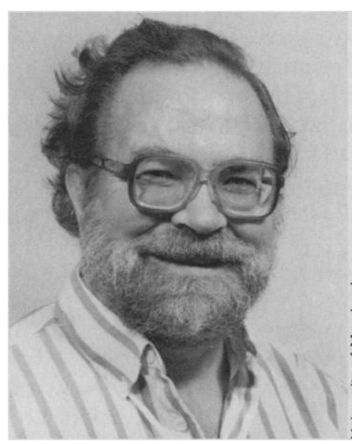
Chaos theory may offer an answer to that question, Ford says. We now know that deterministic systems—those whose behavior is described by mathematical equations—can behave chaotically, which means they act in such a complicated way you cannot predict exactly what they will do in the future. The best you can do is make probabilistic statements about them. A system as simple as the sun, the earth, and an asteroid, for example, can become chaotic. Although all three bodies act according to Newton's laws of motion, the complex influences of the two larger bodies can make the movement of the asteroid so irregular that its future positions can only be described in terms of probabilities.

This may be an important insight, but is it revolutionary? Hardly. It is not even new. A century ago, the French mathematician Henri Poincaré studied the general three-body problem and understood that in certain cases the solutions become intractably complex.

So what is revolutionary about chaos? One answer is that over the past 15 years scientists in a wide range of fields have come to realize that the world is not nearly so orderly as they once assumed. Poincaré may have known or guessed how much of the world is chaotic, but this awareness had not seeped into the general consciousness of the scientific community until recently, and perhaps not even yet. "We tend to think science has explained everything when it has explained how the moon goes around the earth," says Jim Yorke of the University of Maryland, who coined the term "chaos" in the early 1970s. "But this idea of a clock-like universe has nothing to do with the real world."


Joe Schwartz/Georgia Tech

Joseph Ford: *Chaos brings us face-to-face with Gödel's Theorem.*


University of Maryland

Jim Yorke: *Chaos shows we do not live in a clock-like universe.*

Chaos is a mathematical concept that is rather difficult to define precisely, but it can be thought of as deterministic randomness—"deterministic" because it arises from intrinsic causes and not from some extraneous noise or interference; and "randomness" referring to irregular, unpredictable behavior. The appealing aspect of chaos is that it offers a way to understand complicated behavior as something that is purposeful and structured instead of extrinsic and accidental.

Ringleaders of the chaos revolt say that for the past 200 years Western scientists have looked at a messy, complicated world and seen only this "clock-like universe." Classical physics proved so successful, they say, that it ended up limiting the way people look at nature. Now, Yorke says, "chaos gives us a very different picture of the world in which we live."

Thomas Kuhn described the effects of such a shift in scientific perspective in his famous book, *The Structure of Scientific Revolutions*, published in 1962: "Led by a new paradigm, scientists adopt new instruments and look in new places. Even more important, during revolutions scientists see new and different things when looking with familiar instruments in places they have looked before."

The theories of relativity and quantum mechanics sparked the two major paradigm shifts in the 20th century, Kuhn wrote. Relativity vanquished the false distinction between matter and energy, while quantum theory introduced the idea of inherent uncertainty. Will chaos theory beget a third paradigm shift?

Not surprisingly, both Ford and Yorke answer in the affirmative. Other scientists are more skeptical. Paul Martin, dean of applied sciences at Harvard, says, "There have been some interesting ideas, some that were around but that many scientists weren't aware of, but I don't think it's revolutionizing the way we look at science." The essence of chaos—the idea that the behavior of some deterministic systems can only be described statistically—may be news to some people, he adds, but "weathermen knew it 30 years ago, and many more people have realized it in many more areas."

The contribution of chaos theory has been, Martin says, to give researchers an appreciation of just how little complexity in a system is needed to produce complicated phenomena. This in turn gives rise to the hope that researchers will be able to get detailed analyses of some physical systems that previously seemed open only to statistical solutions, he says. "That's an advance, it's not a revolution."

Revolution or not, there is no denying the allure of chaos's cause. In one field after another, researchers have answered its call to arms.

In astronomy, Jack Wisdom at the Massachusetts Institute of Technology has discovered that many bodies in the solar system follow chaotic orbits. The moon Hyperion is tumbling chaotically around Saturn. The gravity of Jupiter can push asteroids in the asteroid belt into chaotic motion, and some of them end up heading toward the earth as meteoroids. Computer calculations show the orbit of Pluto is chaotic.

In physics, Richard Brewer of IBM has placed two barium atoms in an electromagnetic trap. By varying the strength of the electromagnetic field, he can propel the atoms from stability into irregular, chaotic motion and back again.

In chemistry, a number of researchers have analyzed the Belousov-Zhabotinskii reaction, an oscillating chemical reaction, and have seen the concentration of the reaction products vary chaotically over time.

But in a sense, none of these results can be called revolutionary. In each case, the system behaves according to well-understood and accepted physical rules, and researchers have simply found cases where the solutions to the equations behave chaotically instead of with the nice, orderly behavior that had been studied up to then. It is good to know that the real world does indeed behave as the mathematical equations predict, even when those equations have chaotic solutions, but it is not too surprising.

The true revolutionaries are those researchers who are engaged in fields where the mathematical models do not work so well, or maybe do not exist at all, and who are using the ideas of chaos to explain things that standard science cannot.

Ary Goldberger, a cardiologist at Harvard Medical School, is one such rebel. Goldberger studies variations in the rhythm of the heart. He hypothesizes that these fluctuations hold a great deal of information about the health of the heart. Strangely enough, a healthy heart has chaotic fluctuations in its pattern of beating, he says, while sick hearts often are much more regular in their rhythms.

The idea inherent in this approach, Goldberger says, is that a researcher can get a great deal of information by studying the variability of a system in addition to its stable order. For example, he says, two patients can have the same heartbeat statistically but with different dynamics, and their states of health can be quite different. The only way a physician could distinguish between the two patients would be by looking at fluctuations in the heartbeat that are

Art Imitates Chaos

Science usually doesn't have much to say to art. Let's face it, string theory, plate tectonics, and DNA are not likely to send painters scurrying to their canvases. But fractals and strange attractors . . . ahh, that's different.

"There's something inherently appealing about chaos, something fatalistic that everyone can empathize with," says Kevin Maginnis, an artist and president of Kaos Inc., a not-for-profit organization that backs "eccentric or anomalous efforts in art or science." Kaos Inc. is sponsoring a Chicago art show this fall whose theme is chaos, and Maginnis says the response from artists and architects has been enthusiastic.

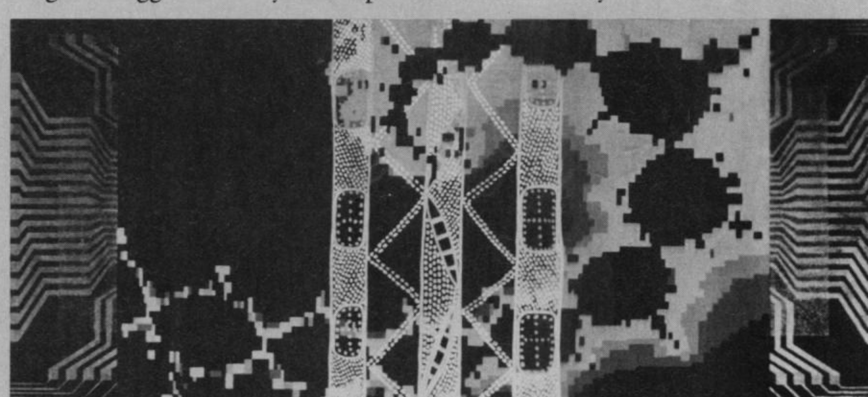
Chaos is appealing to artists, Maginnis says, because it offers a fresh way to view the world. "The challenge is to get art that is influenced by the idea [of chaos] but that is not just illustrative of it," he says. The way to do this is to "take the idea to an intuitive, nonrational level that no scientist can express."

Klaus Ottmann, who is in charge of the visual arts section of the show, sees the appeal somewhat differently. "The main attraction for artists," he says, "is the decorative element in chaos, particularly in fractal geometry." Ottmann, an art critic and curator of exhibitions at Wesleyan University, says that decoration has been downplayed by modernist schools which have emphasized function, but chaos and fractal geometry give artists a chance to have both. "Chaos theory can bring meaning or content back into ornamentation," he says.

Maginnis and Ottmann both emphasize the attractiveness of the yin/yang relationship between chaos and order. The chaos/order dichotomy provides an "open-ended way to organize things" that "allows for spontaneity but is visually very striking," Maginnis says. Some artists, Ottmann says, attempt to "juxtapose order and chaos in a visual field," leading to such combinations as computer-generated fractal images integrated with primitive patterns.

Whatever the attraction, it is not limited to Chicago. After planning his show, Maginnis discovered the New Museum of Contemporary Art in New York City was planning a similar exhibit, and they agreed to host simultaneous shows. From 13 September to 26 November, "Strange Attractors: Signs of Chaos" will run in New York City, while "Strange Attractors: The Spectacle of Chaos" is in Chicago.

Some of the artists Maginnis contacted about the show were already consciously using ideas from chaos in their work, he says, while others recognized echoes of chaos in their work after he described it to them. "People have a natural empathy for chaos," Maginnis suggests. "Everyone's experienced it in one way or another." ■ **R.P.**



Chaos-inspired art: *"Puru Asymptote" by Carter Hodgkin.*

Everywhere You Look, Everything Is Chaotic

The chaos insurgency has opened up fronts in nearly every scientific discipline. Some of the targets are:

■ **Meteorology.** Edward Lorenz at the Massachusetts Institute of Technology got the chaos revolt rolling in 1963 with his demonstration of chaotic behavior in a much simplified model of atmospheric air flow. Meteorologists today accept that chaos in the atmosphere makes accurate predictions impossible more than a couple of weeks into the future, but some hope that chaotic models may eventually make it possible to predict long-term trends in the weather.

■ **Economics.** William Brock at the University of Wisconsin–Madison and Chera Sayers of the University of Houston have used chaos theory to look for hidden order in business cycles. They hope to improve short-range predictions of economic data.

■ **Physiology.** The brain uses chaos as a waiting state, says Walter Freeman at the University of California at Berkeley. Studies of human EEGs show that brain wave patterns become more ordered when a subject is taking in or processing information, he says. Other brain researchers are looking for ways to predict epileptic seizures by analyzing chaotic EEG patterns.

■ **International politics.** Alvin Saperstein at Wayne State University concocted a model for an arms race between two hostile nations. Experiments on a model where both countries introduced antimissile defense systems showed that the situation was chaotic and unstable, eventually leading to war.

■ **Astronomy.** Some variable stars pulsate irregularly. Oded Regev of Columbia University has done numerical modeling of this behavior and found evidence of chaos.

■ **Transportation.** The award for the most down-to-earth application of chaos theory may go to a group of traffic engineers, who, during a meeting in Washington, D.C., in 1988, associated chaos with snarled traffic patterns. Next time you're stuck in stop-and-go traffic on a rush-hour freeway, blame it on chaos. ■ R.P.

usually thought of as extraneous noise to be ignored.

Traditionally, researchers in physiology have tended to look for order and to treat whatever order was available in a system as the most important detail, Goldberger says. If he is correct in believing that fluctuations—disorder—also contain important information about a system, "it's going to transform the way people look at their experiments, the way they look at their data. People will be looking for all these chaos ideas in the data."

But are such new approaches the same as a revolution? Not in the sense that quantum mechanics or relativity was a revolution, says Steven Toulmin, a philosopher of science at Northwestern University in Chicago. Where quantum mechanics opened up an entirely new level of behavior in the physical world, chaos is merely correcting a 200-year-old mistake. "People assumed for more than 200 years that a Newtonian world was predictable," he says. "Chaos shows that this was always a mistaken assumption."

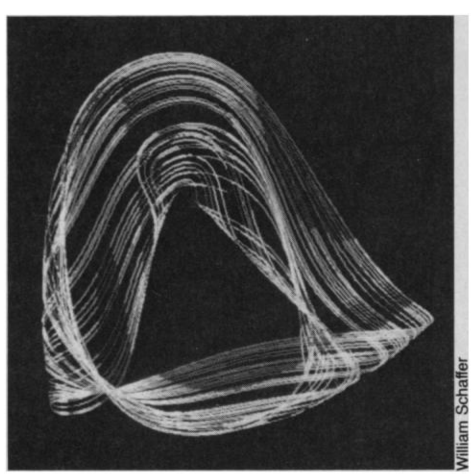
Instead of quantum mechanics or relativity theory, Toulmin thinks chaos is better compared with statistical mechanics, a mathematical tool that can be used to study various physical systems that exhibit statistical behavior. Chaos theory gives us extra intellectual weapons, but not an entirely new world view, argues Toulmin.

On the face of it, Toulmin's point seems hard to argue with. If all that chaos theory offers is the insight that there is more to the world than order and stability and that a complete description of nature must include complicated behavior, then it is not revolutionary. It suggests new lines of inquiry, offers new tools to study irregular behavior, but it is not a new world view.

However, some of the people who have studied and thought about chaos most deeply insist that there is more to come.

For instance, one deep question that has been raised but not answered is: What is quantum chaos? So far, chaos has been seen only in classical systems, and physicists do not even have a good idea of what quantum chaos should look like. But if quantum mechanics is indeed the fundamental theory of nature, it should include chaos in one form or another, since chaos is indisputably part of the natural world. The fact that no one has seen anything that can be identified as quantum chaos may reflect a shortcoming of quantum theory.

Ford, who refers to himself as the Evangelist of Chaos, says he believes chaos theory will fundamentally change our view of the world by "forcing us to face our limitations." One way it will do this, he suggests, is by bringing Gödel's Theorem to bear on physics. Mathematician Kurt Gödel proved that any mathematical system of interest is incomplete—there will always be questions that can be asked but not answered in any particular logical system. "Chaos is, in a sense, Gödel's child," Ford says. Chaos theory proves that there are physical questions that cannot be answered—where Pluto will be in its orbit 1 billion years from now, for instance.



Chaos comes to life *in such computer-generated images as this strange attractor.*

Yorke's vision is broader and less specific than Ford's. To Yorke, the lessons of chaos can be nicely summed up with a line from *Hamlet*: "There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy." Or in Yorke's paraphrase: "Things are stranger than you think."

By this he means that our perception of the world is limited by our understanding of nature. Chaos, he says, promises to liberate this view from the clock-like picture of the universe that has influenced Western science's paradigm for more than two centuries. "One of the disappointments is the way the scientific community has jumped on the idea of order in chaos," says Yorke. "Now that they've found chaos, they want to look for order in chaos."

However, Yorke continues, "If we set our goals at looking for the mundane, then we will find it. The facts are that the universe is much more complicated than we imagine, and if one understands how strange the world is, one begins to look for these strange things." For Yorke and many other chaos scientists, the search is already on for these strange things. ■ ROBERT POOL