CHAOS AND ITS ROLE IN THE BRAIN

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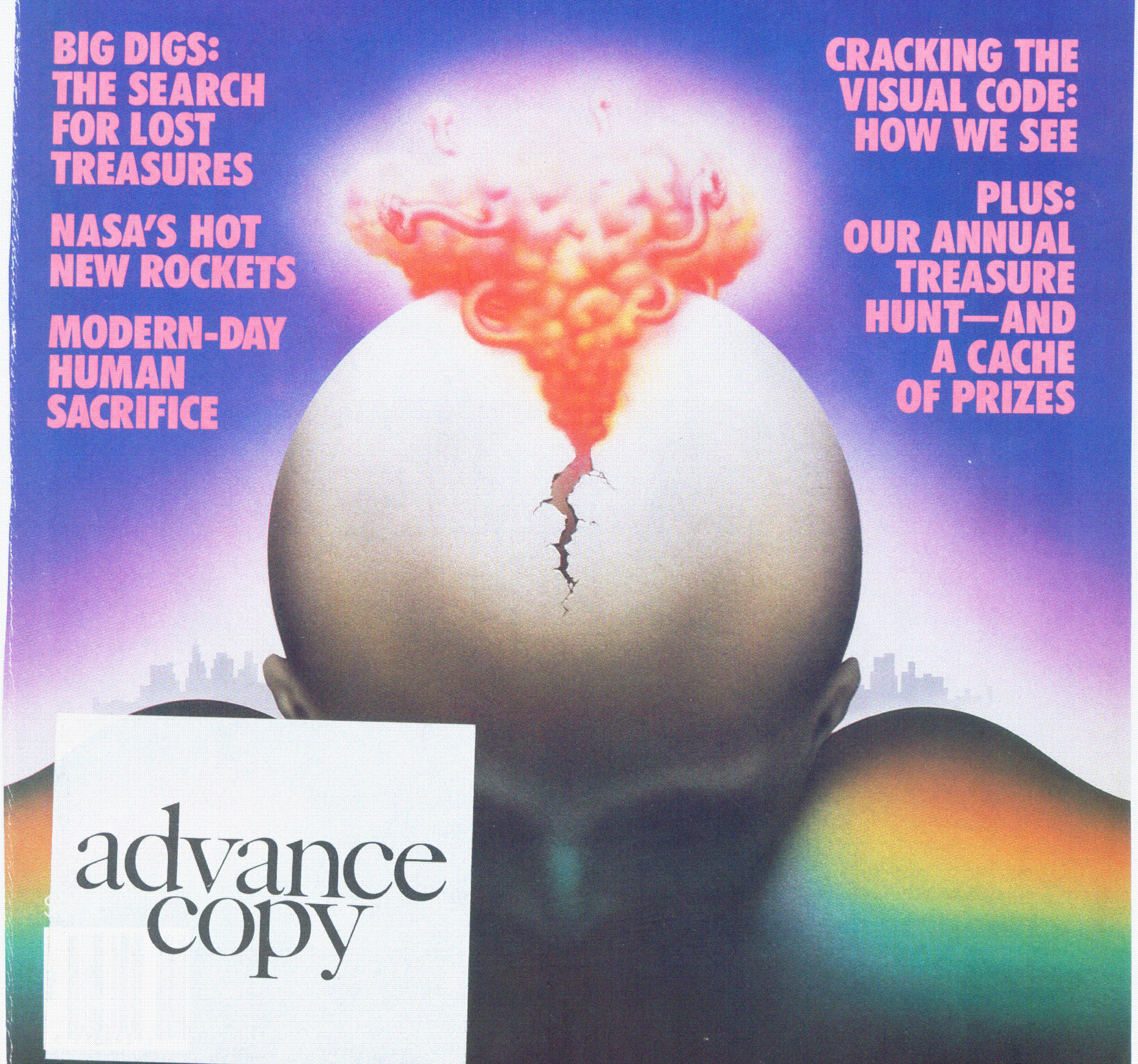

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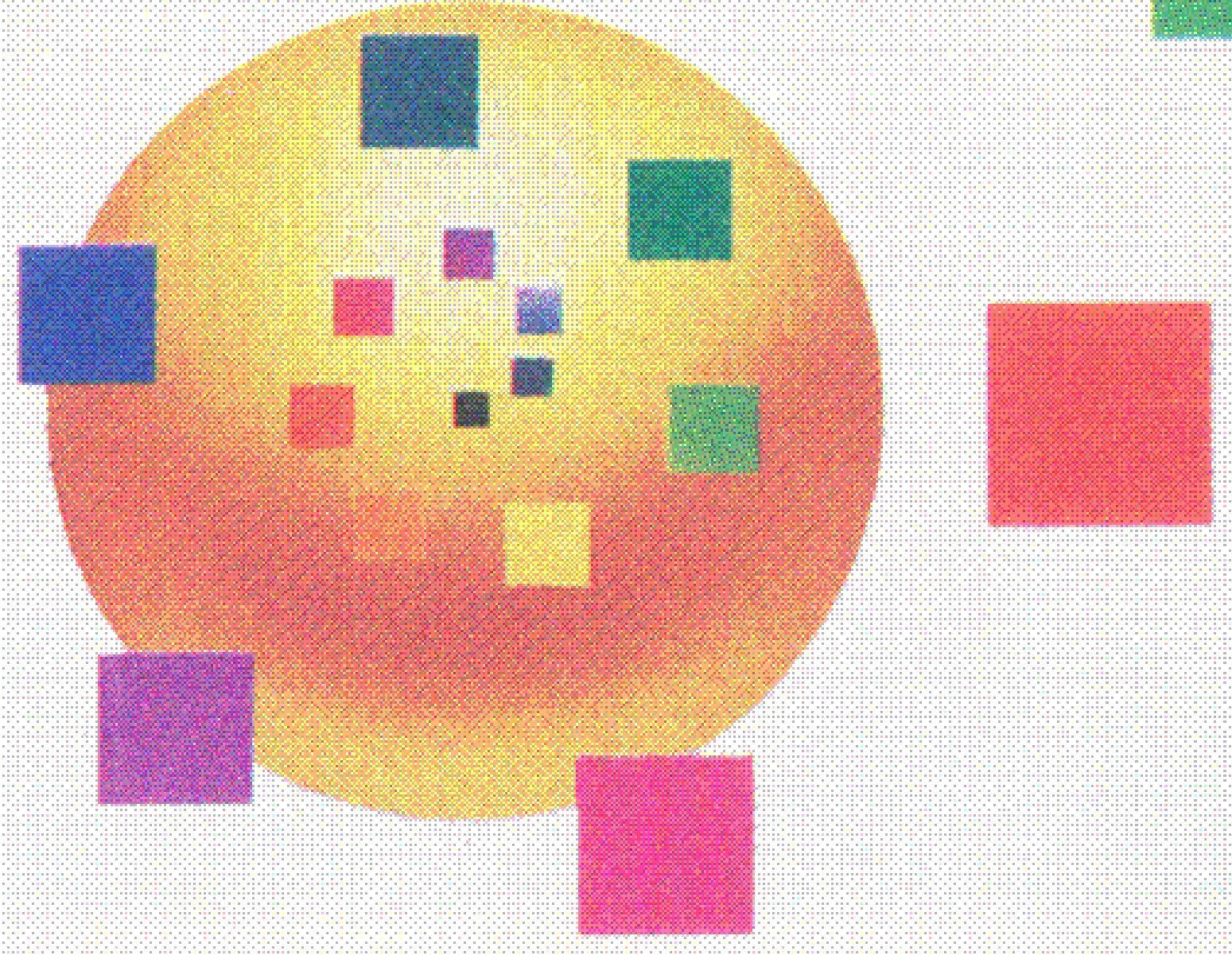

GET SMART: CONTROLLING CHAOS

Disorder, whether on Wall Street or in our minds, may just be a higher form of order

BY KATHLEEN McAULIFFE

Creation came out of chaos, is surrounded by chaos, and will end in chaos.—Anonymous

On the door to Paul Rapp's neuroscience lab at the Medical College of Pennsylvania is a picture of the Wright brothers' historic flight at Kitty Hawk. "I'm building a machine to fly inside my own head," explains Rapp, forty, whose tall stature, thick swept-back hair, and wire-rimmed gaze suggest a cross between a commanding scientific intellect and a die-hard romantic—which may in fact be the case. A self-described "bad poet" and Mahler fanatic, Rapp holds advanced degrees in mathematics and physiology. In keeping with this unlikely mix of passions (or perhaps because of them), he is unabashedly in pursuit of a new cosmology of the mind. His "flying machine": a computer-graphics program driven by mathematical equations from nonlinear dynamics, a new field that has revealed a secret inner order to seemingly chaotic phenomena.

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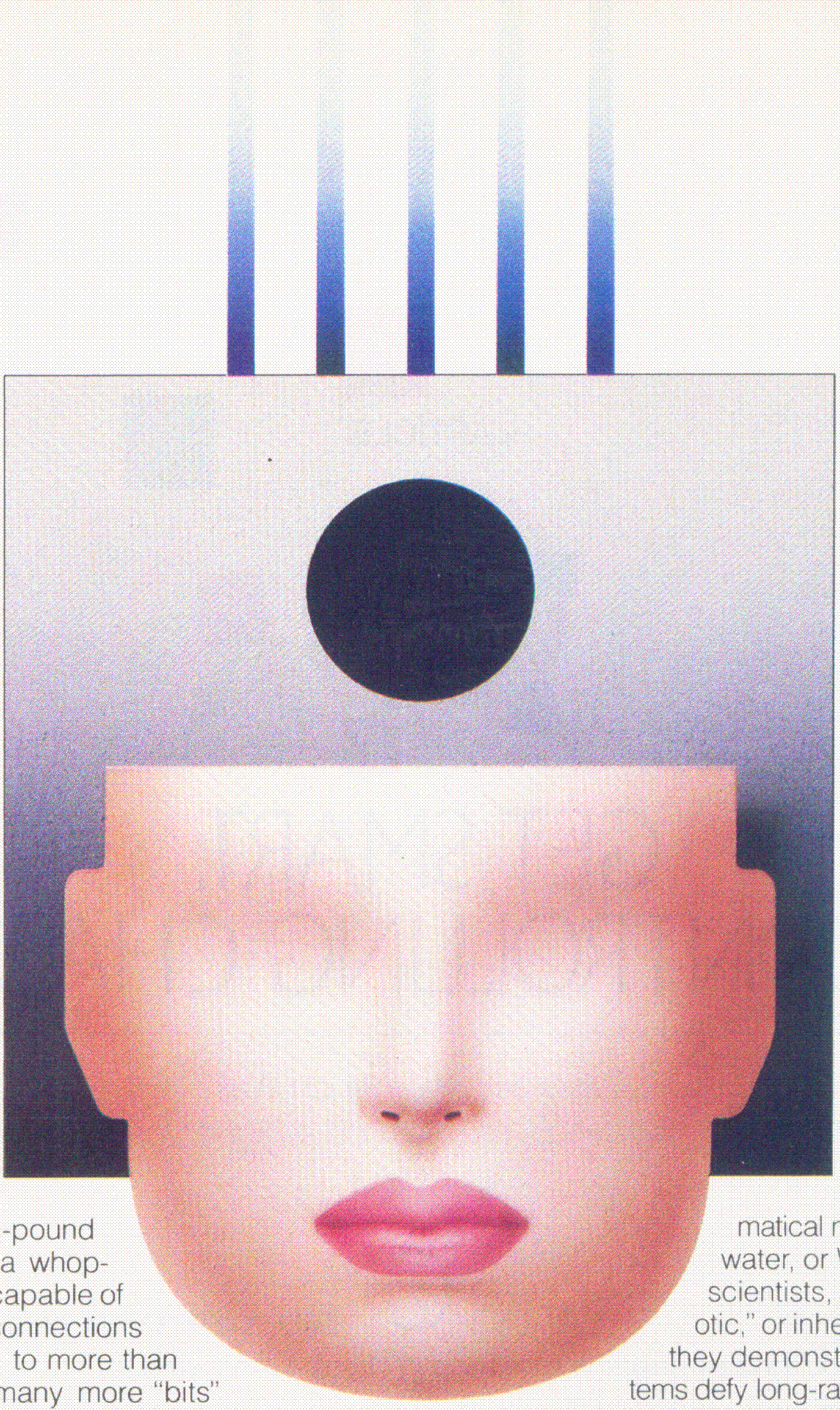


This fledgling science has enthralled diverse specialists—from economists to meteorologists—who seek to understand complex, constantly fluctuating systems. The weather, turbulent water, oscillations in wildlife populations, the rise and fall of market prices—and yes, even the brain—are now being modeled on computers using nonlinear equations. This approach, which has given rise to a body of knowledge called chaos theory, brings clarity to otherwise meaningless numbers. Through these simulations, researchers can sometimes discern simple underlying patterns in complex systems. It is this possibility that draws Rapp and other scientists who dare to contemplate the workings of the human brain. This three-pound bundle of wetware packs in a whopping 12 billion neurons, each capable of forming as many as 50,000 connections with other cells. That adds up to more than 100 trillion connections— or many more "bits" than make up any computer so far dreamed of.

Faced with such complexity, neuroscientists over the last century have approached the brain as they would an intricate machine, taking it apart piece by piece and testing each component. Using this reductionist strategy, they have identified 60 or so neurotransmitters, charted the wiring scheme of major nerve pathways, and recorded the electrical impulses of single neurons. But for all their success, these efforts always fell short of explaining how the individual parts work in concert to produce such global properties as ideas, emotions, acts of will—in short, consciousness. The new mathematical tools raise the hope of finding unifying principles that transcend the gritty details, enabling neuroscientists to step back and scan the bigger picture. "If there is a Holy Grail to neural functioning," says Rapp, "chaos theory will help us find it."

Rapp likens this strategy to a researcher studying China by suspending a microphone over Beijing. "You won't learn Chinese that way," he says, "but you could pick up daily or seasonal variations in the noise level, which would tell you something about the gross pattern of activity of a large urban population." In a similar fashion, says Rapp, chaos theory is revealing variations in the rhythms of vast collections of neurons. These unsuspected patterns, long hidden in the irregular squiggle of the brain's electroencephalogram (EEG), are triggered by problem solving, memories, moods, and neurological conditions ranging from Parkinson's disease to schizophrenia. One of Rapp's claims to fame: He can tell whether a subject is doing simple or more taxing mental arithmetic from an analysis of his brain waves.

Because nonlinear equations can be applied to phenomena on any hierarchical level—from the microscopic to the cosmic—a handful of intrepid researchers are using the same techniques to identify similar patterns in human behavior. By analyzing videotaped sessions of psychotherapy, for example, they have begun to spot trends in patient–therapist interaction—such as an ebb and flow of speech and emotional pitch—that are unique to individuals and highly stable over time. "The explosive freedom we gain from describing reality in mathematical metaphors is breathtaking," says Rapp. "We can discover truths about ourselves that we could never have learned as poets writing in English."

How can man be described in the same mathematical metaphors as the weather, white water, or Wall Street? In the language of scientists, all these phenomena are "chaotic," or inherently unpredictable. Although they demonstrate distinct trends, these systems defy long-range forecasts. You cannot know what you will be thinking two weeks from Tuesday any better than you can predict stock indexes or the ambient temperature. This would seem to be stating the obvious, but until recently, in fact, most scientists ignored or denied this quirky, forbidding side of nature. They preferred Newton's reassuring clockwork universe of frictionless pendulums, of dependable machines, of planets moving around suns in smooth elliptical orbits. Although these "ideal" models are now known to be aberrations of nature—or, as one physicist put it, "as scarce as hen's teeth"—it's easy to see their appeal. With knowledge of the laws of motion and a few starting conditions—such as the position and velocity of an object—scientists can reliably calculate how a system will change over time. With virtual certainty they can determine, for example, when Halley's Comet will return to the vicinity of Earth in the next century or the path of an arrow shot through the sky.

The reason for this orderly predictability becomes apparent from a closer examination of the arrow. From the moment it leaves the bow, the starting conditions (with the exception of air resistance) never again influence its course. Consequently, the arrow and other objects of classical physics follow a smooth, uninterrupted path. On a graph their behavior can always be plotted as a gradually sloping line.

Chaotic systems are not so obliging—hence the term *nonlinear* dynamics. Such phenomena are sustained by complex loops of feedback, in which the outcomes of initial inputs are diverted back into the system at unpredictable points in its cycle. One pendulum swings to and fro with a regular motion, but if it is struck by the ball of a second pendulum before reaching its zenith, both pendulums may begin swinging in a wild, erratic fashion. Similarly, when an ocean breaker bounces off a jetty, it will collide with oncoming waves that variously enhance or diminish its size. In the brain, too, the electrical impulse of one neuron gets unpredictably amplified or dampened by inputs it receives from connected neurons. Such "kick backs" send a chaotic system flying off in a new direction, rather than proceeding in a smooth, even-paced way.

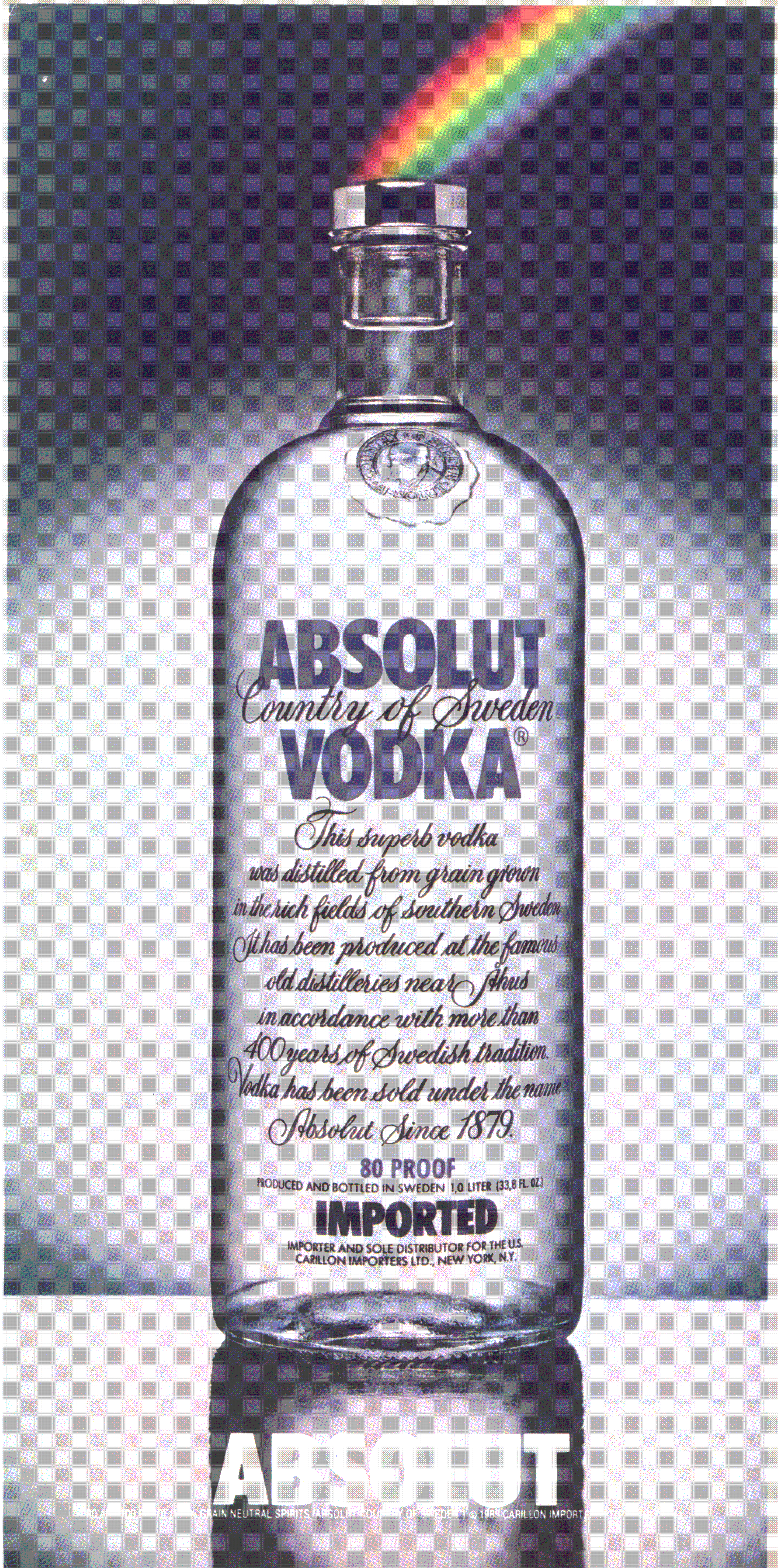
Small wonder that a map of its future course is quickly consumed by a wild tangle of trajectories. This is the image of chaos—of wind, of water, of mind. But to the utter dismay of scientists, it did not turn out to be the unruly disorder everyone feared. What began as a mad jumble of trajectories eventually assumed a form—a ghostly geometry called a strange attractor.

"The first time I ran an EEG signal through a computer that transformed it into a geometric image, I expected something bewildering and ugly," recalls Rapp. "Instead there was this dazzling, filigreed structure slowly revolving in three-dimensional space. It looked like a tulip with multicolored edges, and with each rotation another petal unfolded. I said, 'Look! Look!' " (His colleagues' response, herewith recorded for posterity: "No shit!")

The story of how Rapp became acquainted with this mathematical wonder is really the story of his life. To put it succinctly, it takes a strange mind to appreciate a strange attractor. As the heir to a long lineage of mathematician farmers from Fulton County, Indiana, Rapp may have carried the seeds of strangeness from the very start. Rapp's mother is a mathematician, as were his maternal grandfather and both of his brothers. Even his great-grandfather was nuts for numbers. "Every evening after plowing the farm," says Rapp, "he'd sit down with a mathematical workbook and, in beautiful nineteenth-century script, perform calculations until the sun went down."

Rapp, who still maintains 78 acres of the farm, has carried on these twin family traditions. But he has also taken some detours from this path. As an undergraduate at the University of Illinois in Urbana, he found himself drawn to physiology and poetry. "It dawned on me that the most fascinating thing in the known universe was my mind," says Rapp. "So off I went on a journey of self-discovery, writing poems and trying to learn everything I could about how the brain functions."

After graduating summa cum laude, Rapp still had a yearning for learning, which he pursued in England at Cambridge's prestigious department of applied mathematics and theoretical physics. There, at home in this "wonderful community of unfettered loonies," he submerged himself in the mathematics of



"biological oscillators": biochemical reactions that can suddenly be amplified or diminished through complex feedback loops. The equations describing the reactions were nonlinear, which meant that Rapp soon found himself overwhelmed by pages of unruly numbers.

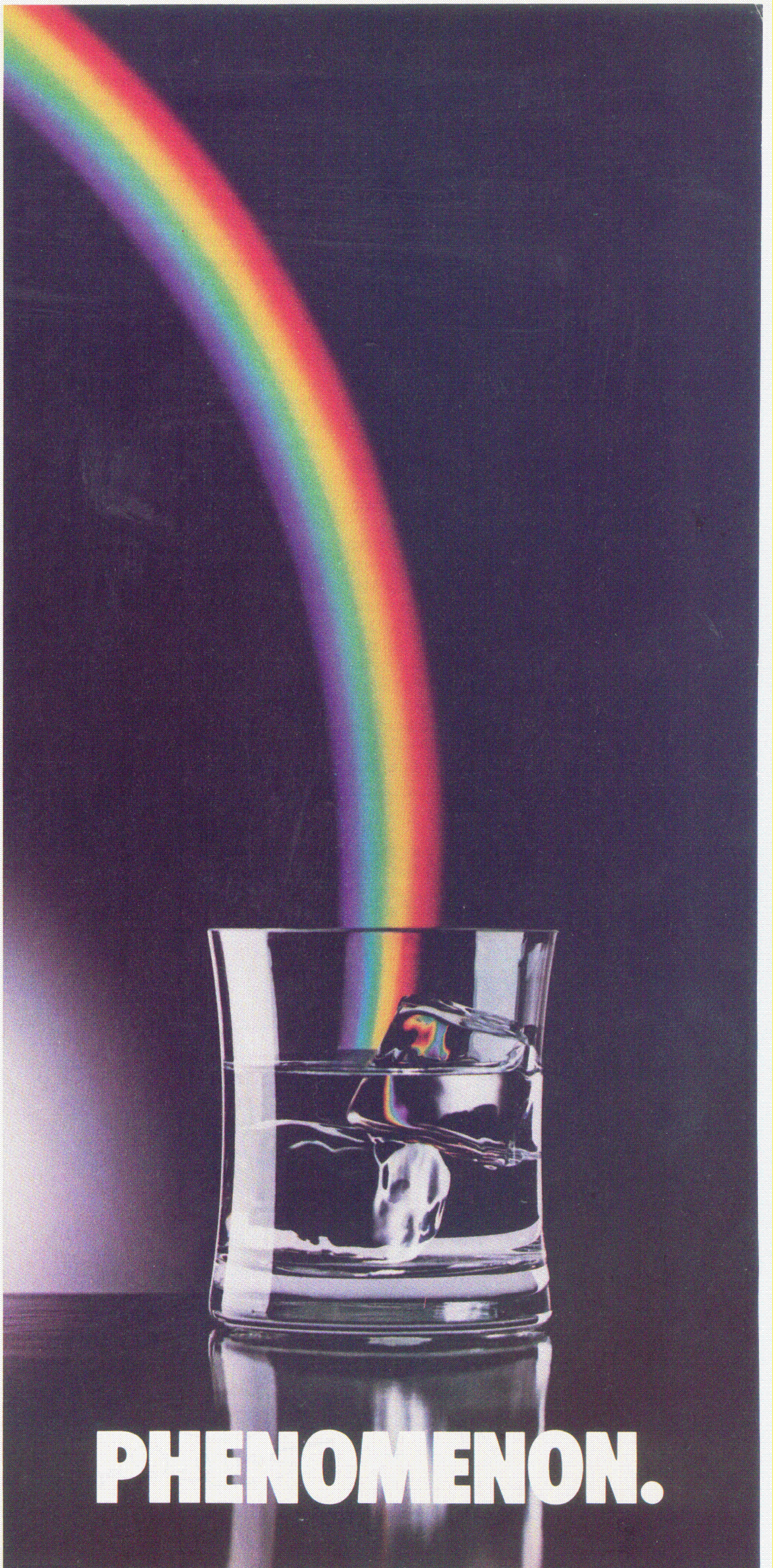
It was now the mid-Seventies, and as Rapp wrestled with this intractable problem, he learned of an extraordinary paper that had gone unnoticed for more than a decade. Published in an obscure meteorology journal in 1963, the paper was by Edward Lorenz of the Massachusetts Institute of Technology, whose main fascination was trying to understand climatic patterns. Although this was hardly an interest of Rapp's, the three equations Lorenz had used to model the weather were nonlinear. What's more, he had found an intriguing way around their staggering complexity.

After struggling with the equations and getting nowhere, Lorenz plugged them into a computer—still something of a novelty for research laboratories of that era—and used a primitive graphics generator to display the results.

Rapp's heart thrilled at learning the outcome: The mathematical points first spun into one orbit and then looped around to a second orbit, coiling in on themselves like a snake. The points jumped back and forth endlessly between the two orbits, never repeating the same path. In time, however, the thicket of trajectories traced out a structure that resembled a domino (the little black eye mask worn at Venetian carnivals), with the orbits settling around the two "eyeholes." As Rapp immediately grasped, there was a hidden structure to chaos. Although Lorenz didn't give a name to his discovery, his computer had brought to life the first strange attractor. Rapp now looked to this artificial creature for his redemption—his escape from madness.

What exactly is a strange attractor, and how can a structure emerge out of disorder? "Think of it," says Rapp, "as an idealized state toward which an unpredictable—that is, strange—system is attracted." The structure stems from the fact that the behavior of the system is not totally random. Rather, the system vacillates erratically within a particular range, or norm.

Consider climate. There are record high and low temperatures that define what is normal weather on this planet. In Lorenz's model that range is specified by the boundaries of the domino, and motion never occurs outside of them—for example, it never goes above 200° F. But within the "normal" range, it can be any temperature—hence motion on the surface of the domino is unrestricted. Put another way, a strange attractor is a symbol of "bounded madness": It has strictly defined boundaries, but within the boundaries anything goes.



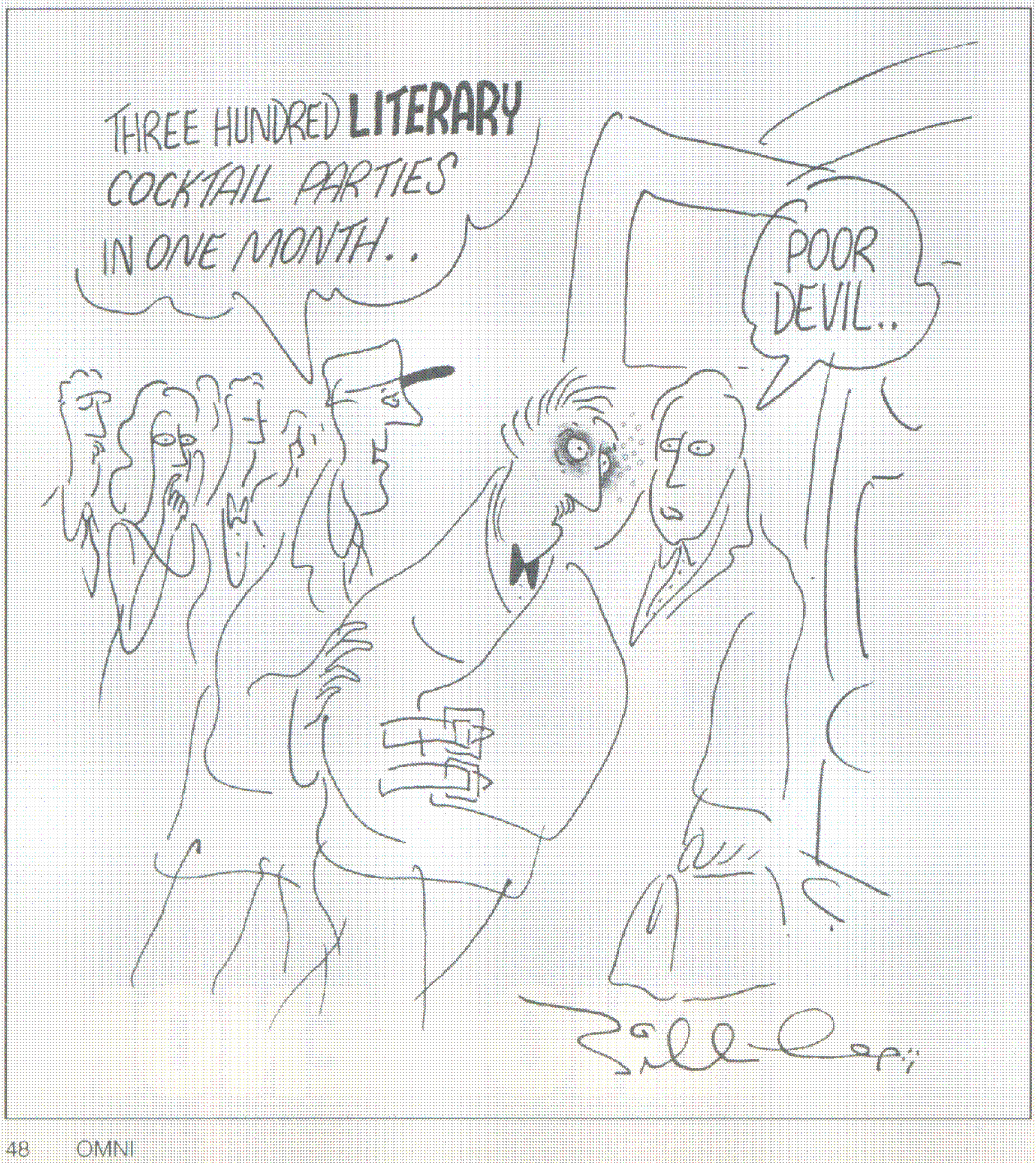
These insights have led to a friendlier view of chaos. Ironically, what was once shunned as a terrifying mess has come to be embraced as a higher form of order. Like the balance of yin and yang stressed in Chinese cosmology, chaos now connotes a paradoxical state between rigid organization and randomness, between predictability and chance. Some have even seized its bounded madness as the perfect New Age metaphor for emotional stability. Psychiatrist Arnold Mandell, an early proselytizer of chaos theory who is now in the department of mathematics at the University of California at San Diego, has a T-shirt emblazoned with the words BOUNDED CHAOTIC MIXING PRODUCES STRANGE STABILITY. Translation: A well-balanced individual is flexible (capable of vacillating among a wide range of mood states) yet controlled (the moods always stay within certain bounds).

To be sure, chaotic fluctuations in the brain may occasionally be harmful—or so research on schizophrenia suggests. But the latest findings show that in many instances, the brain functions normally—and even optimally—in a chaotic state.

After analyzing the EEGs of humans, Rapp has also come around to this friendlier view. "When we are healthy and alert, the interval between electrical waves is never rigidly fixed," he reports, "but always vacillates around a certain frequency range." Moreover, when we are mentally challenged, the interval between the electrical waves becomes even more variable—or chaotic. This suggests, in Rapp's opinion, that chaos "may actually be highly beneficial during problem solving."

To demonstrate his point, he shows the results of an EEG study in which subjects were asked to count backward mentally from 200 either in steps of seven (i.e., 193, 186, 179. . .) or in steps of two (i.e., 198, 196, 194. . .). From the electrical tracings alone, it is impossible to distinguish between the two experimental conditions. But as Plato prophesied, "Geometry will show the soul toward truth." When the EEG signal is fed into a computer and transformed into an abstract structure—a strange attractor—Rapp can immediately see a difference: When subjects are subtracting by seven, the strange attractor is rich and complex. It looks vaguely like the starship *Enterprise* in *Star Trek*. In the much simpler task of subtracting by two, the strange attractor suddenly flattens out in one plane, resembling a Frisbee seen from the side. Mathematically the structure is in fact less complicated, or "chaotic." Clearly, the greater the mental challenge, the more chaotic the activity of the subject's brain.

In a related experiment, the subject is asked to press a button every time he hears a high-pitched tone but to ignore medium- and low-pitched tones. The strange attractor, or geometric structure related to his EEG, is most complex during the presentation of the nontarget tones. Rapp's explanation: As soon as the subject hears the high-pitched tone, his brain converges on the signal and goes into a simpler, less chaotic state of activity.



What does all this mean? In Rapp's opinion, chaotic activity may be an asset in problem solving. "You want to be able to scan as wide a range of solutions as possible and avoid locking on to a suboptimal solution early on," he explains. "One way to do that is to have a certain amount of disorderliness, or turbulence, in your search."

Rapp supports his theory by pointing to the deliberate use of random functions in state-of-the-art neural nets: computer programs designed to simulate human intelligence. To illustrate how this works, he asks us to imagine a bumpy terrain that represents all possible energy states of the brain. In the neural net the current state of the brain is specified by an imaginary ball rolling about the surface. The ball is attracted to the valleys because the rules of the program presume that the best solutions to a problem conform to the lowest energy states—that is, states in which strongly connected "neurons" in the system will fire together. To find a good solution to a problem, the ball thus must ignore shallow energy basins in favor of the deepest valleys—the best solutions. How does it do that?

This is where randomness comes in handy. If the ball is set loose, explains Rapp, it will simply roll to the bottom of the nearest valley—probably not the best solution. But if it is given a little random jiggle, the ball will be able to explore many more valleys before settling down. In this way the neural net may find a better solution.

The results can be entirely unexpected in the same way that human problem solving can lead to unforeseen conclusions. A neural net designed by John Hopfield of the California Institute of Technology, for example, uses its random search system to "free-associate": Its "memories" mix and mingle in new combinations, crudely imitating what a psychoanalyst does for a living. It is also capable of learning. For example, the neural net can be "conditioned" to avoid noxious food in the same way that the common garden slug, *Limax,* does. That may not be impressive by human standards, but for a computer, it is a remarkable achievement.

Intriguingly, outside of artificial intelligence such random search systems have been used by computers to generate very good—though not necessarily the best—solutions to problems in the least amount of time. For example, tele-

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sion takes place," says astrophysicist Robert Noyes of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, "that is roughly equivalent to two billion one-megaton nuclear bombs." When flare particles finally reach Earth, our planet's magnetic field intercepts the charged particles and diverts them toward the poles. There they collide with the atoms and molecules of the upper atmosphere to create the spectacular and haunting auroras—the northern and southern lights. Over the past year, flare activity has ignited auroras visible as far south as the Bahamas.

The flares that pelted Earth last March astonished scientists with their ferocity, setting our magnetosphere wobbling like a great bowl of Jell-O. Moving magnetic fields, as you may remember from high-school physics, induce electric currents in lengths of conductive material, including—as millions of Canadians found out—power lines. Last March's geomagnetic storm overloaded Hydro-Québec's electric power grid: Equipment fried and all of Quebec went dark.

Not long after the Quebec blackout, more than 5,000 artificial satellites were lost. Flares dump energy into our atmosphere, causing it to heat up and expand and placing additional drag on satellites in low Earth orbit. On March 18 the U.S. Navy's satellite tracking system—the air traffic control for space—found that thousands of satellites had strayed from their predicted orbits. Dozens of weather and survey satellites—which need to be precisely aligned with their earthbound targets—careened out of control, their onboard gyroscopes spinning frantically to compensate. It took the Navy several days to locate the stray satellites and to plot their new orbits. "A few of the satellites have maneuvering control systems that can readjust their orbits," says astrophysicist Don Neidig of the National Solar Observatory in Sunspot, New Mexico. "The rest stay where they are."

Drag from solar flares helped send the *Skylab* space station plummeting prematurely to Earth in 1979, and the present sunspot cycle has downed NASA's Long Duration Exposure Facility two years ahead of schedule. Don Neidig says space scientists are now concerned that increased drag due to solar maximum activity will shorten the expected life span of such costly satellites as the Hubble Space Telescope. To minimize drag, NASA upped the planned altitude of the telescope from 320 to 330 nautical miles, pushing the satellite-launching capability of the space shuttle to its limit.

The sun's bag of tricks seems bottomless. Helping guard us from solar sorcery is the Space Environment Service Center, a division of NOAA. The center keeps a vigilant watch over the sun, collecting data from satellites, its own solar telescope in Boulder, and a global network of solar observatories. By phone, by fax, and by satellite broadcasts, the center issues warnings of heavy solar activity to a lengthy list of clients.

Thanks to NOAA forecasts, power companies can be alerted to geomagnetic storms and can reduce the loads on their power grids to lower the risk of outages; operators of long-range communications equipment—including the FAA, the Department of Defense, and the Voice of America—can anticipate and prepare for solar interference; and geophysical exploration teams that use magnetometers to sniff out untapped mineral resources can take into account the likelihood that their readings are tainted by geomagnetic storms.

Although NOAA can alert its customers to solar activity in progress, space scientists are generally helpless when it comes to making long-range forecasts. The upcoming maximum is a good case in point: Joe Hirman and his cohorts at NOAA thought that a relatively subdued maximum might follow the strong one that peaked in 1979. Their guess was dead wrong. If this year's maximum continues to spout extraordinarily strong flares, it will become the biggest on record.

"What it boils down to is that we don't have a good quantitative model of solar activity," says George Withbroe, associate director for solar and stellar physics at the Harvard-Smithsonian Center for Astrophysics. But with billions of dollars worth of satellites on the line, devising prediction models has become a critical concern. Withbroe, for example, is currently chairing a commission to study the effects of solar activity on satellites. "Predictions have basically been a black art," admits Withbroe. However vital that knowledge may be, it will be some time before scientists forecast solar activity with even the questionable reliability of your TV weatherman.

CREDITS

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phone switching networks use this strategy to minimize the number of channels in use. The reason: To find the absolute minimum, rather than a close approximation, would take a supercomputer days to calculate. Clearly, here—and, if Rapp is right, in the brain—the better solution is the best solution.

On introspection, at any rate, many people view these programs as a satisfying description of their own mental processes. As the late physicist Heinz Pagels noted in his last book, *The Dreams of Reason,* "Rarely [do I solve problems] through a rationally deductive process. Instead I value a free association of ideas, a jumble of three or four ideas bouncing around in my mind. As the urge for resolution increases, the bouncing around stops and I settle on just one idea or strategy."

Still another possible role of chaos in the brain is suggested by the research of Walter Freeman at the University of California at Berkeley and his collaborators Christine Skarda and Viana di Prisco. They did electrode recordings from the olfactory bulbs of rabbits that had been taught to discriminate various odors. Their work suggests that the background activity of the bulb is chaotic, representing many patterns of neuronal firing. When the rabbit recognizes an odor, the background activity converges on a single neuronal firing pattern—displayed as a strange attractor on a computer—that is always the same for that animal. On the other hand, if the animal is exposed to an odor never before encountered, the background activity becomes even more chaotic than normal. Only gradually, over several exposures paired with rewards, does the rabbit's olfactory bulb come to converge on a new strange attractor pattern, which is henceforth associated with that odor. "Chaos," says Freeman, "is a wonderful state of readiness for an animal because it ensures continual access to all learned sensory patterns at any given instant."

As a bonus, chaos theory may also offer answers to the big questions that torment scientists and humanists alike. To wit, what is the source of novel ideas? How can we have free will and still be slaves to scientific laws that govern the behavior of all matter?

Troubled by man's autonomy, scientists in earlier centuries resorted to invoking a little man inside our heads—a homunculus—who was issuing all the orders. In a less than satisfying revision, contemporary theorists have merely replaced the homunculus with an automaton—a mindless brain that functions like your desktop computer, obediently following the commands of an almighty (but so far elusive) program. Unfortunately, automatons do not make very good free thinkers.

How can we be creative and willful and still be law-abiding citizens of the universe? The random elements given so much free play in chaotic systems may be the key to the solution, according to physicist James Crutchfield at the University of California at Berkeley. From chance beginnings, he notes, a tiny fluctuation in the brain's activity might be blown up into a new global pattern—a thought—that manifests itself as innate creativity. Moreover, should this thought entail a decision to act, says Crutchfield, our behavior will be "perceived to be the exercise of will."

As Rapp is quick to point out, however, man is not alone in tapping this mainspring of novelty. Lest humans think they have a monopoly on creative power, consider cloud formations, the spiral arms of galaxies, and the whorls and vortices that spring up spontaneously around a rock in a stream. Marvels Rapp, "The beauty of it all comes down to what sounds like a Zen koan—controlled randomness."

The notion that chaos might have a constructive side has also carried over to medicine, where it has prompted fresh insights into the causes of several neurological conditions. Once doctors put aside negative stereotypes of chaos, a surprising vision opened up to them: While a few diseases—notably schizophrenia—might indeed be the result of too much chaos in certain brain systems, many so-called "disorders" turned out to be exactly the opposite. The problem was *too much* order. The complex rhythms of the nervous system had been replaced by a regimented beat or even drowned out altogether.

A startling example—albeit one that involves the nervous system only indirectly in its role in controlling heart contractions—nonetheless demonstrates the dramatic shift in scientific thinking. Cardiologist Ary Goldberger of Harvard Medical School recently discovered that the normal rhythm of the heart is surprisingly erratic. What's more, the rhythm of the heart's natural pacemaker may be more regular in people who are at high risk of cardiac arrest. In summarizing his findings, Goldberger says, "The healthy heart dances, while the dying organ can merely march."

There is a dramatic parallel in the brain. Rapp holds up two EEG charts. One has large, smoothly rounded waves that are evenly spaced. The other is a wiggly line that rises and falls haphazardly into sharp peaks and valleys. The smooth, regular waves, it turns out, were recorded from an epileptic having a seizure. The irregular squiggle was produced by the brain of a healthy person.

On learning that beautifully symmetrical waves could rack the body in violent spasms, Alan Garfinkel of UCLA's department of kinesiology was struck with an idea. An expert in movement disorders, Garfinkel had long puzzled over the debilitating tremors that plague victims of stroke and Parkinson's disease. He wondered, Could an affliction of the nervous system similar to epilepsy be at the root of their problems?

Fortunately for Garfinkel, patients admitted to UCLA's hospital are routinely given electromyograms (EMGs)—a procedure for recording the electrical activity of the neuromuscular system. "There were a stack of these EMGs in a back room," he recalls, "so I decided to take advantage of them." A careful analysis of these records confirmed his hunch: Patients with normal motor control had nerves that pulsed in a chaotic fashion, whereas the EMGs of spastic patients demonstrated much more regular bursts of electrical activity.

"Contrary to intuition," says Garfinkel, "you need desynchronized firing of nerve cells in order to achieve smooth movement." He draws an analogy to a platoon of soldiers crossing a bridge. To prevent destructive vibrations from collapsing the bridge, the soldiers break rank.

“To the utter dismay of scientists, what had begun as a jumble of trajectories—the disorder everyone feared—eventually assumed a form, a ghostly geometry called a strange attractor.”

Neither epilepsy nor tremors would appear to have anything in common with the extreme mood swings characteristic of depression. Yet a loss of "healthy variability" in neural activity has been implicated here, too. According to Cindy Ehlers, a neuroscientist at the Scripps Clinic in La Jolla, California, a normal person will undergo erratic and relatively mild fluctuations in mood on an almost daily basis. "But in the depressed patient," says Ehlers, "there is a loss of some kind of control mechanism, so that over time their behavior starts to look extremely periodic or rhythmic." She has seen some manic-depressives, referred to as rapid cyclers, who very regularly flip mood states every three weeks. The chronic depressives, on the other hand, seem to be, in Ehlers's words, "stuck in a monotonic state." No matter what's happening around them, they feel despondent.

A healthy, alert mind, Ehlers's research suggests, is nonperiodic—or in a state analogous to Mandell's bounded madness. "There's some rhythmicity in order for the body to function correctly, to be in sync, but it's not too rigidly locked in to these rhythms or the person would lose versatility and adaptability," she concludes.

After hanging out with bag ladies at a public park in San Jose, California, in the early Eighties, psychiatrist Roy King began to suspect that schizophrenia might also enslave its victims in a nightmarish cycle. Although his laboratory was a little unconventional, the park had a major advantage over the local psychiatric ward: The bag ladies, King explains, constituted a rare reservoir of untreated schizophrenics.

Seated on a park bench with watch in hand, he timed their comings and goings. "One moment you'd see them pushing their shopping carts around, talking out loud to themselves, and flailing their arms," he recalls. "A little while later they'd be withdrawn, sitting alone by themselves on a bench." It turned out there was a method to their madness: They'd switch from frenetic activity to a catatonic state roughly every 20 minutes. King knew that the neurotransmitter dopamine had long been implicated in schizophrenia. So he played around with some equations that modeled the uptake and release of dopamine by neurons in the brain. Plotting his data points, he came up with a nonlinear, U-shaped curve. To his delight, it showed that a flaw in neural feedback mechanisms would cause dopamine levels to rise and fall every 20 minutes. "That's what I believe caused their behavior shifts," says King, who is now at Stanford University. "The malfunction was analogous to what happens when a microphone has its amplifier on too high, causing feedback in the form of a high-pitched squeal."

Would chaotic fluctuations in dopamine levels restore normal behavior? In this instance, King cautions, they might make the schizophrenic even worse. "The model," he says, "indicates that the brain is healthiest when dopamine remains at the same level."

Beyond increasing our knowledge of brain dysfunction, the new mathematical models are suggesting novel approaches to preventing, or at least reducing, disease symptoms. Rapp, for example, can sometimes see a shift in the brain's electrical activity before an animal has an epileptic seizure. There is a dramatic loss of complexity in the strange attractor associated with the EEG signal—a sign that millions of neurons are beginning to pulse in unison.

If the same observation holds up for humans, it could serve as an advance warning to doctors that modifications are needed in the patient's treatment regimen. "Rather than waiting for you to have another seizure to determine if the drug is doing what it's supposed to," explains Rapp, "I want to be able to say, 'I don't like the way your brain waves look today. Let's increase the dosage of your anticonvulsant.' "

Still more futuristic applications of chaos theory have captured his fertile imagination. The mathematician–poet–physiologist–farmer is also an aviation enthusiast, which undoubtedly inspired this novel concept: "It might be possible," Rapp says, "to develop an EEG-monitoring system that would detect when a fighter pilot is about to black out during violent maneuvers that force blood out of his brain." Just before falling unconscious, he reports, there is a precipitous decline in the brain's chaotic activity—a phenomenon that might be detected by electrodes fitted into the pilot's helmet. The information would then be relayed to an onboard computer, which would correct the trajectory of the plane to reduce the gravitational forces on the pilot.

Similarly, Rapp can envisage electrode-studded headware for air traffic controllers, nuclear plant operators, radar monitors, and other professionals whose unwavering vigilance is critical to the safety of a large sector of the public. Here again, chaotic fluctuations in the EEG might be used as a measure of mental alertness.

As the mathematics of nonlinear dynamics advances, Rapp anticipates that computers will be able to detect increasingly subtle changes in brain waves as a result of drug-induced states, learning, disease, and aging. Of course, just where this will lead can be discerned only in vague outline, like the shimmering dimensions of a strange attractor. But at least one likely outcome of these advances, in Rapp's opinion, will be better techniques for diagnosing learning disorders, Alzheimer's disease, and other neurological conditions that produce a confusing array of symptoms.

Anesthesiologists, too, might use computer-aided analysis of EEGs to ensure that surgical patients remain in a safe range of unconsciousness—not so anesthetized that they are in danger of lapsing into a coma but still far from a state of registering any pain. (According to Rapp, it's not uncommon for patients to begin to stir on the operating table during surgery, prompting the anesthesiologist to rush to administer an additional dose of anesthetic.)

On the therapeutic front, he predicts the same technology could become an indispensable tool in speeding the development of new drugs to treat the brain. As he elaborates, "Chemicals that restore the normal electrical patterns of the brain would be obvious candidates for further testing and refinement."

As if that weren't enough to keep one man busy for a lifetime, Rapp is branching off from his EEG studies to undertake a bold new initiative—arguably his most ambitious yet. He's searching for unifying theorems that underlie psychotherapy—or in his own words, "I'm trying to shine a candle on this very dark, mysterious rite of passage."

The plan is to analyze behavior in the context of therapy just as though it were an EEG tracing—only instead of charting the voltage spikes of neurons, his computer-graphic wizardry is being used to track the verbal exchanges between individual patients and their therapists. "Basically," he explains, "we're trying to discover if there are mathematical patterns—such as strange attractors—underlying aspects of the patient–therapist interaction. And if so, are some patterns of interaction more likely to help the patient than others?"

> *‘If you think humans have a monopoly on creativity, consider cloud formations or the whorls and vortices that spring up spontaneously around a rock in a stream.’*

Clearly, Rapp is excited by the prospect of charting the seething caldron of human feelings with nonlinear equations. "This is where all the aspects of my life tie together," he says. "We're dealing with this very human process—where the poet inside me feels at home—but I get to also function as a mathematician and a neuroscientist."

Joining him in his quest for psychotherapy's unifying principles are psychiatrist Robert Langs and mathematician Anthony Badalamenti of the Nathan S. Kline Institute for Psychiatric Research in Orangeburg, New York. Although most psychotherapists begin with a grand theory, which they then attempt to test, Rapp and his collaborators have taken the opposite tack. The researchers begin at the microscopic level of behavior and build theories from the bottom up rather than the top down. "They're building the world's first psychoscope," observes Ralph Abraham, a mathematician and celebrated chaos theoretician at the University of California at Santa Cruz.

With the patients' permission the team begins by videotaping therapy sessions, which are then broken down into 15-second segments and scored on such items as, Who is talking? For how long? Is there continuity of theme? Are there sexual references? Is the material derived from intellectualization or fantasies and dreams? Next the team of researchers plots a graph of how the therapist's interventions and the patient's responses change over time.

What can they see through the lens of their psychoscope? The picture is far from complete, but so far the patient and therapist appear to function as a unit, with repetitive patterns of communication—as unique as a signature—emerging over successive sessions. "There may be strange attractors characterizing these interactions," reports Langs, "but we won't know for certain until we've carried the analysis further."

One likely example of a strange attractor is a peculiar trend in the length of time each speaker talks in succession over the course of the therapeutic session. This time sequence appears random at first inspection but in fact follows a nonlinear progression called the Box–Jenkins model, long familiar to economists, who use it to describe market trends. The finding is so new that the scientists can't say whether it is unique to psychotherapy or applies more broadly in human communication.

Of more immediate relevance to psychotherapy, according to Langs, is the unexpected finding that therapists generally keep the discussion in rigid, narrow channels. In reaction, patients struggle to push back these limits by introducing disturbing images from dreams, fantasies, and other "unconscious modes of communication."

After scoring the first 100 lines of transcribed dialogue between six different patients and their therapists, Langs found the level of unconscious communication was higher in all instances before the therapists intervened. His interpretation: "Despite their training, psychoanalysts have a dread of unconscious meaning, which really translates into a dread of chaos."

In one illustrative case a young woman admitted to her therapist that she fantasized about doing physical harm to her mother. He responded with a rhetorical question: "You've built a different life for yourself, haven't you?"

The woman paused for several seconds, her train of thought interrupted, but soon brought the conversation back to her obsession with harming her mother. She noted that her father, in real life, had been physically abusive to her mother before abandoning the family. That might explain, she continued, why her mother had such a negative attitude toward sexual intimacy—"viewing it almost as rape."

"I guess your father leaving you was

a great loss," the therapist interjected.

This time the patient did not attempt to steer the conversation back to her violent images but kept to familiar, nonthreatening topics. Consequently, a graph of her scores on several parameters—including frequency of sexual references, diversity of themes, and emotional intensity of material—suddenly flattened out. "Our preliminary analysis of the data," says Langs, "would suggest the interaction between the patient and therapist had become more static—or less chaotic."

Paradoxically, it is more often the patient who initiates dynamic change during therapy, says Langs, "because so long as he or she remains locked in to a single pattern, there's not much chance of evolving to a new way of thinking. It is only by looking at unconscious meaning, by going through that storm of chaos, that a patient can resolve conflict, arriving at a higher level of order."

In addition to these findings, Rapp has uncovered a subtle pattern of indoctrination behind psychotherapy, a nonlinear trend that became apparent when the same patient was seen separately by three therapists with different ideological bents.

"The pattern of interaction basically conforms to the doctrinal philosophy of the particular therapist," says Rapp. In classical psychoanalysis, for example, therapists expect continuity of subject matter—which is exactly what happens in 90 percent of their exchanges. A communicative therapist, on the other hand, expects many discontinuities in verbal behavior and questions about therapy itself. What's more, that's just what the therapist gets. "Ironically," says Rapp, "both classical and communicative therapists base their approach on free association and view themselves as nondirective. But our graphs tell a different story: Patients very rapidly adapt to the typically unvoiced expectations of the therapist."

As the researchers acknowledge, they have barely begun to extract meaning from the mountains of transcribed texts of therapy sessions. Very simply, it's a lot easier to collect data than to make sense of the findings. In keeping with their doctrinal philosophy, however, the researchers are confident that out of this unruly disorder, a higher level of order will emerge, paving the way for more effective methods of psychotherapeutic intervention.

Aside from the practical benefits of applying nonlinear formulas to the brain and behavior, there are enormous aesthetic rewards. Or so claims Rapp, who has been spending much of his spare time transforming his own brain waves into "cortical sculptures"—strange attractors that metamorphose according to his mental states. Of late he has even expanded into multimedia effects through the addition of music as a backdrop to the pulsating strange attractor on his computer screen. It is genuinely the music of his hemispheres, for Rapp converts the frequencies of his brain's electrical waves directly into sound waves.

"Basically," explains Rapp, "I begin by wiring up my brain and then run the EEG output through a digital converter that simultaneously turns the signal into strange attractors that can be both seen and heard."

What does an abstract geometric structure sound like? It depends on what Rapp's thinking, of course. At rest—if he's daydreaming, for instance—Rapp likens the music of his mind to a diggery do, a hollow aboriginal instrument that produces a resonant hum when banged with a stick. When he engages in mental arithmetic, causing the strange attractor on his video monitor to explode in a fireworklike display, the auditory accompaniment also rises to a crescendo. Can his brain's output match the tonal density of Mahler's symphonies? Not quite, or as Rapp admits, "It sounds more like a bee trapped inside a diggery do."

There's presently a long delay between the recording of his brain waves and their conversion by the computer into his *art chaotique*. But eventually Rapp intends to do away with the time lag by devising a system of instant feedback. "Then I'll get to hear and see the strange attractors simultaneously in my head—all in *real time*," emphasizes Rapp. "In other words, while still hooked up to the EEG machine, I'll be able to respond to all the sounds and visual images my mind just produced in an endless loop of creativity."

In a characteristic fit of rhapsody, he adds, "Just think what it would be like if the mind's imaginings could torrent out without the existence of musical instruments or paintbrushes."

His eyes light up like those of a preacher imploring his congregation to marvel at the miracle of salvation. To Rapp, one suspects, the creation of nonlinear art forms is much more than a hobby. It's a transcendental experience—a religion.

"Philosophers and great religious thinkers of the last century saw evidence of God in the symmetries and harmonies around them—in the beautiful equations of classical physics that describe such phenomena as electricity and magnetism," he says. "I don't see the simple patterns underlying nature's complexity as evidence of God. I believe that *is* God. To behold a strange attractor, spinning to its own music, is a wondrous, spiritual event." ∞