Is It Healthy to Be Chaotic?

Chaos may provide a healthy flexibility to the heart, brain, and other parts of the body. Conversely, many ailments may be associated with a loss of this chaotic flexibility

This is the third in a series of stories on chaos in various fields of science. Still to come are articles on quantum chaos and chaos in fluid dynamics.

A HEART ATTACK leaves an unmistakable signature in an EKG. Before the attack, while the patient's heart is beating normally, the EKG is the epitome of stable regularity—a mostly flat line interrupted every second or so by a quick up-and-down blip marking the beat. Suddenly ventricular fibrillation sets in, and the tracing jumps about as if it will fly off the page. Seen side by side, the difference between the normal rhythm of the heart and the pathological cadence of the heart attack is striking.

An epileptic seizure seen in an EEG looks remarkably similar. The EEG of a normal brain, although not as regular as a healthy heart signal, has a sedate rhythm of its own. It wanders up and down, up and down, with its height varying only slightly from peak to peak. When the seizure hits, the EEG shifts into starker, more violent motion.

The heart attack and the seizure can be thought of as "dynamical diseases," a term suggested by McGill University physiologists Leon Glass and Michael Mackey for pathologies marked by a shift in the body's normal rhythms. Doctors know of a number of such rhythm disorders, including fluctuations in white blood cell counts in leukemia victims and Cheyne-Stokes breathing, a periodic quickening and slowing of respiration that often accompanies congestive heart failure.

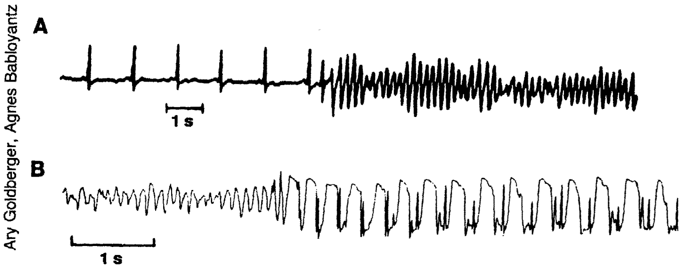
But what are the body's normal rhythms? The standard answer is that a healthy body has rather simple rhythms. In this view, the different parts of the body either tend to homeostasis, where interrelated systems reach an equilibrium, or else they have some simple periodic behavior, such as the rhythmic beating of the heart. A disorder will have a more complicated, less controlled tempo.

A revisionist school of thought wants to turn that interpretation upside down. According to this still developing idea, a healthy physiological system has a certain amount of innate variability, and a loss of this variability—a transition to a less complicated, more ordered state—signals an impaired system.

This healthy variability is not just random, uncontrolled fluctuation, however. It is a certain well-heeled type of disorder called chaos. Although the precise mathematical definition of chaos is somewhat complicated, its presence in the body can be characterized by two things. First, it is there by design—it is not caused by the random firing of neurons, for instance, or by haphazard chemical reactions. Second, the behavior of a chaotic system is complicated and unpredictable. Although the system may stay within certain limits—a heart rate might remain within 60 to 80 beats a minute—the complexity of its behavior defies specific predictions.

"Maybe chaos is the natural way to put together the various things in the body," suggests Ary Goldberger at the Harvard Medical School. Goldberger, who has done extensive analysis of normal and diseased hearts, argues that chaos provides the body with the flexibility to respond to various stimuli. "Healthy systems don't want homeostasis," he says. "They want chaos."

Ary Goldberger, Agnes Babloyantz



A change in rhythm *appears in (A) a heart attack, and (B) a petit mal epileptic seizure.*

Researchers who study chaos and other complicated dynamics in the body say better insight into the body's rhythms, both healthy and impaired, will help doctors diagnose and predict illnesses better. The ultimate goal is improved medical care based on understanding how different treatments affect the dynamics of the human body.

The best documented example of physiological chaos to date comes not from the human body but from in vitro studies of heart cells from embryonic chicks by Glass, Alvin Shrier, and Michael Guevara. A cluster of these cells will beat spontaneously in a regular, innate rhythm, and a strong electrical stimulus applied to the aggregate causes the next beat to be earlier or later than normal. (In mathematical terms, it resets the phase of the heartbeat.)

If the heart cells get a periodic series of electrical shocks, they are pushed by two timekeepers, their own internal rhythm and the rhythm of the shocks. The resulting heartbeat depends on the timing of the electrical stimulus. In some cases, the heart cells will beat in time with the stimulus—once for each jolt, or twice, or several times; or perhaps three times for every two jolts, or some other fractional value. But in other cases, the cells fire seemingly at random and never settle into a periodic rhythm. This is chaos—a complex, nonperiodic behavior that results from physiological control mechanisms.

The experiment shows chaos can be induced artificially in a physiological system, but does it occur naturally? A number of researchers say yes.

"Healthy sinus [heart] rhythms are chaotic," Goldberger says. Although a heartbeat seems quite regular and periodic, it actually varies irregularly from second to second, minute to minute, and hour to hour throughout the day. By analyzing these variations mathematically, Goldberger concluded they are chaotic—they are complicated and unpredictable, but they result deterministically from the way the heart regulates its beating rather than being random fluctuations.

Further, by comparing the EKGs of normal, healthy individuals with those of heart patients, Goldberger discovered that healthy hearts show more variability in their beating than do sick ones. The healthy ones are in a sense "more chaotic," he says.

Part of Goldberger's mathematical analysis of the heart rate involves calculating its frequency spectrum, which measures the different rhythms in the fluctuation of the heart rate. For instance, the heart rate of some ill patients is almost constant; in this case, the graph of the frequency spectrum is approximately zero, indicating there is almost no fluctuation in the heart rate. The heart rate in other patients speeds up and slows down in a regular pattern, which shows up in the frequency spectrum as a single spike because there is only a single rhythm to the fluctuation.

Goldberger says frequency spectrums for healthy individuals show rhythms of all periods arranged in a $1/f$ distribution. (In a $1/f$ spectrum, the strength of a rhythm of a particular frequency is inversely proportional to some power of its frequency.) The $1/f$ distribution is suggestive—but not conclusive—evidence of chaos in the normal heart, Goldberger says.

The strongest argument for cardiac chaos, he says, lies in the structure of the heart. The nerves that carry electrical signals to the ventricles of the heart are structured in a series of branchings, much like the root system of a plant. Configurations like this are called fractal structures, and the entire heart (as well as other parts of the body, such as the lungs and circulatory system) seems to be fractal in design. In a 1985 paper, Goldberger, Valmik Bhargava, Bruce West, and Arnold Mandell showed how the fractal structure of nerves directing the heart could lead to a $1/f$ spectrum in the heart rate. "If you accept that our anatomies are fractal, it's only a small leap to say the day-to-day workings of these systems are fractal," Goldberger says, and fractal behavior and chaos are two sides of the same coin.

Goldberger's work has been poorly received by much of the medical community. "The issue of whether fibrillation is chaos is in my mind a non-issue," says one well-known researcher in cardiac dynamics. "Chaos is fashionable, but interest in chaos has really gotten ahead of the facts." Even Glass, who demonstrated chaos in the chick heart cells, believes the case for chaos in normal, healthy hearts is far from proven. "Certainly the heart can change its rate a lot, but I haven't seen any evidence that this variability is associated with deterministic chaos." He points out that a $1/f$ frequency spectrum does not necessarily imply chaos, and says he thinks the heart's fractal structure "has absolutely nothing to do with chaotic rhythms."

Many of the objections center on the difficulty of proving that fluctuating physiological behavior is actually chaos and not just the accidental result of some random signals in the body. While chaos detractors admit the body may have complicated dynamics, they argue that the fluctuations studied by Goldberger are probably just the normal noisiness and irregularity of any biological system.

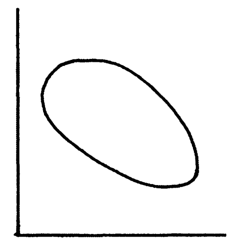
The case for physiological chaos does not stop at the heart. For instance, a number of researchers claim to have found chaos in

The Footprints of Chaos

Tracking down chaos in the body is a bit like tracking down Bigfoot—plenty of people claim to have seen footprints, but no one has quite managed to display the big guy in a cage. The difference is that instead of impressions in the dirt, the tracks of chaos are patterns in some physiological measurement, such as electrical activity in the heart or the brain.

To visualize these patterns, scientists use so-called phase space plots. The advantage of such a plot over an EEG, for example, is that the phase space plot gives more qualitative information about a pattern. One can often tell at a glance whether the footprints are of chaos or just some more mundane creature.

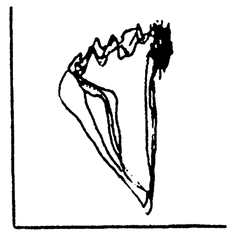
A simple example of a phase space plot is the figure obtained by plotting the EEGs from two different parts of the brain, say from electrode A and electrode B. A point on the plot tells what the A potential and the B potential were at one point in time. In the first graph at the right, the potentials are mapped for five different times, and the points are connected to give a sense of continuity. The position along the horizontal axis gives the A potential, and the position along the vertical axis gives the B potential. The resulting figure is a visual representation of how the pair of electric potentials changed from moment to moment.



The simplest thing a phase space plot can do is stay at one point the whole time. This happens only if the A and B potentials remain constant. Since the only time this happens is when the patient is dead, this case is of little interest.

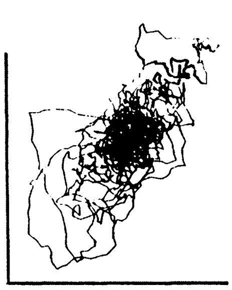
The next simplest thing a phase space plot can do is go around in a loop. This would correspond to the EEGs repeating themselves in a cyclic pattern—the neurons monitored by the EEGs would go through a certain pattern of firing that lasted, say, a fraction of a second and they would repeat that pattern over and over.

In the body, things are not so elementary, but still there is often a discernible pattern. The third figure at right, from a study by Walter Freeman at the University of California at Berkeley, plots a pair of EEG traces from a rat during a seizure. The plot is relatively simple because the brain wave patterns tend to freeze up and become repetitious during a seizure.


Walter Freeman

A phase space plot can be made in any number of dimensions, not just two, and more complicated behavior generally needs more dimensions to display it. In practice, many of the phase space plots are generated from only one EEG (or EKG or other measurement) instead of several, and a technical trick is used to form a pattern that has approximately the same appearance as if several measurements had been used.

Besides the qualitative information available in a phase space plot, one can calculate numbers that give a specific measure of how chaotic the pattern is. One such number is the dimension of the pattern, which, roughly speaking, indicates how much space a figure takes up and is a measure of the complexity of the figure. A point has dimension 0, a simple loop has dimension 1, and a chaotic pattern has a higher dimension that is not a whole number. Generally, the higher the dimension, the more complicated the pattern. The last pattern on the right, generated from an EEG of a human during deep sleep, is obviously more complicated than the one from a rat during a seizure. Its dimension is approximately 4, and the phase space plot should be done in five dimensions to show off the pattern completely.


Agnes Babloyantz

If this sounds less complicated than tracking Bigfoot, it is not. Calculating the dimension accurately involves a number of technical difficulties, and getting a meaningful number, says Rapp, is "difficult, except when it's impossible." ■ **R.P.**

EEG signals. Chaos, they say, may play a role in the brain similar to the one Goldberger proposes in the heart—it provides a healthy variability that allows the organ to respond quickly to a variety of stimuli.

Agnes Babloyantz at the Free University of Brussels has analyzed EEGs of normal brains and brains undergoing epileptic seizures and has concluded that both signals exhibit chaos. In addition, she found that a normal brain is much more chaotic than one undergoing a seizure, which implies that an epileptic attack is accompanied by a loss of variability in the brain's electrical activity.

Technically, Babloyantz looked at phase space maps for each EEG and calculated their dimensions (see box). In normal brains during deep sleep, the dimension was about 4, as compared with about 2 during an epileptic attack. EEGs taken while the patient was awake were much more chaotic than those during sleep, and Babloyantz was unable to measure the dimension. She concluded that the normal EEG of the brain is quite complicated, but it has much simpler behavior during deep sleep, and in seizures it becomes very regular and periodic.

Walter Freeman at the University of California at Berkeley argues that chaos serves the brain as a ready state, keeping it primed to accept new inputs. The normal background neural activity of the brain is chaotic, he suggests, and mental activity takes place as an imposition of patterns on this chaotic background.

Freeman's evidence came out of studies of EEG signals recorded from rabbits' olfactory bulbs as they were exposed to odors to which they had been conditioned to respond. In work with Christine Skarda of the Ecole Polytechnique in Paris, he looked at EEG tracings from 64 probes arranged on a patch of the olfactory bulb and found that a given odor elicited a particular spatial pattern of EEG responses. The patterns were fixed in each rabbit, but they varied from rabbit to rabbit for the same odor.

Freeman and Skarda examined the background activity of the olfactory bulb from which the odor-recognition patterns arose, and developed a simple model of the olfactory system that produced background activity very similar to that observed in the rabbits. The model also reacted to odors much as the rabbit brains did. Because the background activity of the model was chaotic, the researchers concluded that the background activity in olfactory parts of the rabbits' brains was also chaotic. Freeman and Bob van Dijk have since reported similar EEG activity in the visual cortex of monkeys.

"Chaos provides the system with a deterministic 'I don't know' state within which new activity patterns can be generated," Freeman and Skarda wrote in a paper summarizing their conclusions from the rabbit experiments. With the brain in a chaotic state, it can quickly switch into any other pattern, such as the patterns generated when the rabbit is presented with an odor it has been conditioned to. "In the olfactory system, the chaotic background state provides the system with continued open-endedness and readiness to respond to completely novel as well as to familiar input."

Work by Paul Rapp at the Medical College of Pennsylvania fits in well with Freeman's ideas about how the brain functions. Rapp calculates the fractal dimension of EEGs taken from human subjects doing various tasks. Just as Freeman discovered in rats and Babloyantz in humans, Rapp says he found that "the dimension of brain electrical activity changes in response to changes in cognitive activity."

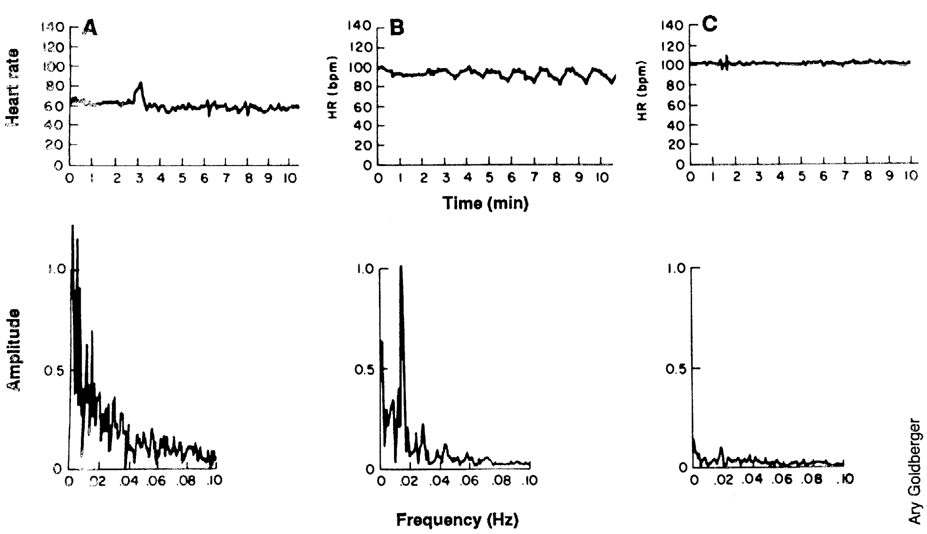
In one experiment, Rapp recorded EEGs for subjects resting with their eyes closed and then again when the subjects were asked to do a mental task: counting backward from 700 by sevens. The dimension of the resting EEGs was about 2.3, and it rose during the tests to approximately 2.9, indicating that a more alert mental state corresponds to a higher dimensional EEG. Rapp says the change in dimension is reproducible.

In a second set of experiments, Rapp exposed subjects to a random series of tones, high-pitched and low-pitched, and asked them to count either the number of high tones, ignoring the low tones, or vice versa. He says he can distinguish accurately which tone the subject hears by looking at the EEG—the tones the subject have been asked to count will cause a lower dimensional EEG than the ones they can ignore. That is because, Rapp says, when the subject hears the target tone, the brain converges on that signal and goes into a state of lower complexity; when the subject hears the nontarget tone, the brain is still working, waiting for the next tone, and stays in the higher dimensional waiting state.

In addition to the electrical activity of the heart and the brain, researchers suggest that chaos may play a role in various other physiological systems. In some patients with leukemia, for example, the number of white blood cells fluctuates dramatically from week to week. Goldberger says this may represent a loss of chaos—normal, healthy people have chaotic fluctuations in their levels of white blood cells, he says, while the cancer patients' levels oscillate cyclically.

Alan Garfinkel at the University of California at Los Angeles suggests that chaos in the body may be a way to avoid strictly periodic behavior, which could be very destructive. This function of chaos, which he calls "active desynchronization," is analogous to the way a group of soldiers breaks step before crossing a bridge so that their march does not resonate with the bridge and cause it to collapse. In muscle activation, for instance, "if individual motor units were to fire periodically, they might tend to synchronize, producing undesirable tremor. Hence, there may well be an active desynchronization mechanism in sustained contraction that spreads out the motor unit timings to fill the time interval of the activity."

Goldberger suggests that Parkinson's disease—which is characterized by uncontrollable tremors in the muscles—may well be caused by a loss of variability in some system. And, he speculates, "aging may involve a loss of variability and spectral reserve, a



Heart rate and frequency spectrum *for three types of heartbeat: (A) normal; (B) rhythmic, associated with Cheyne-Stokes breathing; and (C) nearly constant.*

loss of dimensionality." Youth is more chaotic than old age.

Experiments on pituitary cells grown in vitro have shown that healthy cells obey the chemical orders of their natural regulators, but tumor cells have a rhythmic activity that does not respond to the regulators. Their behavior is locked into a fixed rhythm.

Even the most enthusiastic researchers in the field believe it will be a long time before the increasing understanding of the body's complicated dynamics will pay off with better diagnostics and treatment. "The gap between lab and clinic will be very great," Rapp says. But some of the possible applications are already being discussed.

The first are likely to be diagnostic. Goldberger hopes that by testing for lowered dimensions in EKGs, doctors eventually will be able to pick out those patients most at risk of a heart attack. The same type of test might be able to predict the approach of a seizure in epileptics.

Insight into the body's rhythms might also help improve the effectiveness of current treatment. Glass and Mackey in *From Clocks to Chaos: The Rhythms of Life* (reviewed on page 675) suggest that one of the reasons the survival rate for patients with chronic myelogenous leukemia is no better now than it was from 1910 to 1948 is the oscillations in the numbers of white blood cells, which doctors do not take into account in treatment. "One possible explanation is that some patients die because of the therapy much sooner than if they had been left alone, while others have their life-span increased," they write. Understanding the natural rhythms of the white blood cell control system could lead to a more effective therapy, they suggest. Eventually, doctors might use their knowledge of natural physiological rhythms in such procedures as setting a pacemaker, administering insulin, suppressing tremors, treating epileptics, or even adjusting out-of-sync circadian rhythms.

■ ROBERT POOL

ADDITIONAL READING

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Collision and Cannibalism Shape the Galaxies

Collisions among galaxies are turning out to be a frequent event; they may even explain why galaxies are the way they are

LIKE CORPORATIONS caught up in a frenzy of leveraged buy outs, galaxies seem to spend their lives amidst the constant chaos of collision, disruption, merger, and outright cannibalism.

Indeed, observations increasingly suggest that the brightest and blandest galaxies, the blob-like ellipticals, are in fact the biggest cannibals of all: they are cosmic conglomerates that achieved their present bulk by the simple expedient of swallowing everything in reach. And at least a few astronomers now argue that *all* galaxies grew this way, including our own.

"[The evidence] is not nearly a proof. But it is tantalizing," says François Schweizer of the Carnegie Institution of Washington, who has done a good deal of the observational work in this area, and who recently gave an invited review talk at the meeting of the American Astronomical Society in Boston.* Sharing the podium on that occasion was Alar Toomre of the Massachusetts Institute of Technology, who was has long been a leader in the theoretical analysis of galaxy collisions.

Schweizer and Toomre noted that the basic idea of colliding galaxies is an old one. After all, the very fact that galaxies are randomly darting around at hundreds of kilometers per second means that collisions are inevitable. Moreover, astronomers have known for generations that certain close pairs of galaxies are connected by bridges and streamers of stars. Such galaxies are obviously interacting.

However, the full significance of collisions was not really appreciated until the early 1970s, when Alar Toomre and his brother Juri Toomre of the University of Colorado in Boulder performed a series of pioneering computer simulations of the process. By varying such details as the velocities, the masses, and the relative orientation of the colliding galaxies, the Toomre brothers found that pure gravitational interactions could produce the most amazing variety of effects—everything from simple bridges of stars, to long "rat tails" arcing off at odd angles, to circular "smoke rings" of stars orbiting over the poles of the remnant galaxy at right angles to its main rotation. Furthermore, every one of these effects had already been seen in the sky, where they had seemed so incomprehensible that astronomers began to speculate about mysterious explosions and totally new physical principles. The most famous compendium of such objects, *The Atlas of Peculiar Galaxies* compiled in the 1960s by Halton Arp of the Max Planck Institute for Astrophysics in Munich, reads in retrospect like a textbook on collision phenomena.

In the years since then the art of simulation has improved markedly, says Toomre, as better algorithms and faster computers have allowed researchers to model the colliding galaxies with more precision and realism. And in the meantime, says Schweizer, observational evidence for the ubiquity of collisions has continued to pile up.

When quasars are studied with modern imaging techniques, for example, one often finds that these brilliant energy sources are buried at the center of disturbed galaxies possessing loops and streamers exactly like those in the computer models. The presumption is that the galaxy has recently suffered a collision. And indeed, this interpretation fits in well with the prevailing theory of quasars. The idea is that a quasar's ferocious luminosity is generated by a billion-solar-mass black hole, which pulls in gas and stars from the surrounding galaxy and then converts much of their mass into radiant energy just before swallowing them. The theory presumes that the ill-fated stars and gas can somehow be nudged out of their stable orbits in the host galaxy and deflected into the black hole. And collisions, of course, are an excellent way of doing just that.

Still another piece of evidence regarding the frequency of collisions was provided in 1983 by the Infrared Astronomy Satellite (IRAS), which made the first full-scale survey of the sky at infrared wavelengths. Among the sources detected by IRAS was a large population of galaxies that appeared to be unusually bright in the infrared. Few of them had been bright enough to attract

*The 173rd meeting of the American Astronomical Society, 8 to 12 January 1989, Boston.