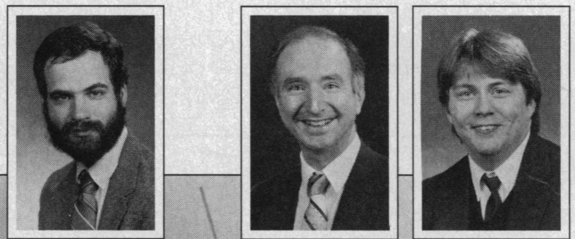
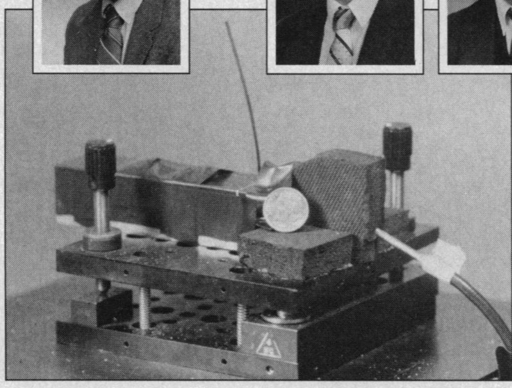
# Engineering Dogma Gives Way to Chaos

*Last year a group of theorists suggested a way to control chaos. Now two groups of experimentalists have proved it can be done, potentially opening up numerous applications*

"I'M ABOUT TO VOICE YOUR WORST NIGHTmare," says physicist Bill Ditto, speaking to an audience consisting mostly of engineers. The previous speakers had given example after example of engineering dogma: To make an electronic circuit, composite material, or any other kind of physical system, you must design it so that a force on the system will produce a proportional response—and that means keeping out nonlinearities, particularly chaos. Now comes Ditto to explode the dogma: "I want your materials to be as nonlinear as possible," he says. "Instead of telling you how to avoid chaos, I'm going to explain how to use and control chaos."

The audience, at the University of California at Santa Barbara's January conference on "smart" materials, can't believe what it is hearing—at first. But by the time Ditto finishes explaining how to control chaos, some of the skeptics have become enthusiasts.





**Chaos controllers.** *Steven Rauseo, Mark Spano, and Bill Ditto with their magnetic nudger.*

Ditto is one of a handful of experimentalists who argue that chaos—extremely complicated behavior that seems random but actually has an underlying order—can be turned to advantage in engineering systems. And they are not just theorizing: Ditto's group at the Naval Surface Warfare Center (NAVSWC) in Silver Spring, Maryland, and another Navy research team have recently conducted two experiments that hint at many potential applications. In particular, they have for the first time controlled chaos and synchronized two independent chaotic systems. Explains Naval Research Laboratory physicist Louis Pecora: "[Previously] people have stayed away from nonlinearities because they didn't know quite what to do with [them]." With the new results, says Pecora, who is leading one of the two Navy teams, "I think that will [begin to] change."

Indeed, Pecora and Ditto say some of their recent developments could someday be applied to signal processing, materials, chemical plants, and even cardiac pacemakers. And they are winning converts. "I think [their work] has enormous potential," says Mike Shlesinger, director of the physics division at the Office of Naval Research. Adds Frank Moss, a physicist at the University of Missouri: Ditto's work "really is the hottest topic going."

The key to their work is that chaos, though apparently random, actually consists of an infinite number of different periodic motions, or orbits; usually, a system will move from one motion to the other, ad infinitum. Ditto and his colleagues Mark Spano and Steven Rauseo found a way to pick one of these motions and lock on to it.

The general idea was first suggested last spring by University of Maryland physicists Edward Ott and Ceslo Grebogi and mathematician Jim Yorke in a paper in *Physical Review Letters*. Because even the tiniest change in a chaotic system can lead to a huge effect later on—a property known as "extreme sensitivity to initial conditions"—the Maryland group reasoned that if you apply a tiny "push" at just the right moment, you might be able to make a wide variety of chaotic systems do your bidding. The idea attracted a lot of attention, but many argued it would be impossible to implement in practice.

Ditto, Spano, and Rauseo were intrigued. At NAVSWC the three had been studying magnetoelastics—materials that change their length and stiffness when exposed to a magnetic field. If you stand a long, thin piece of this ribbon on its end while applying an oscillating magnetic field, the ribbon, not always able to support its own weight, will sway back and forth in a manner similar to an inverse pendulum. But if the magnetic field is large enough, this motion is chaotic not periodic.

The Navy group decided to try to control the chaos in the system by applying a second magnetic field to the ribbon. First, they picked the motion they wanted the ribbon to have, waited until the ribbon was moving in roughly the desired way, then applied a series of small perturbations to the field. Somewhat to the researchers' surprise, the ribbon's motion was directed into the desired pattern. Spano likens the method to balancing a ball in a saddle: If the saddle stays still, the ball will roll off, but if one keeps adjusting the saddle slightly, the ball will stay in place. "We thought it was going to be extremely difficult, but actually it was very easy," Ditto says of their work, which was first published in the 24 December 1990 *Physical Review Letters*.

Ditto, Spano, and Rauseo have so far nudged just one simple chaotic system to behave in a directed fashion, but they say that in theory their technique could ultimately have broad applications. "You should be able to apply this to any system in which you can measure [certain basic aspects of it's motion]," Ditto says. And you don't need perfect accuracy: They have found that the nudges can be off by a factor of two in magnitude or also slightly off in timing, and it will still work. Possible uses, Ditto speculates, include controlling unwanted vibrations in aircraft or spacecraft, selecting frequencies from a chaotic circuit, mixing chemicals, and maybe designing an advanced pacemaker.

While the NAVSWC group has caught the most attention, their colleagues a few miles down the road at the Naval Research Lab have also chalked up a first in manipulating chaos: Lou Pecora and Tom Carroll recently managed to synchronize two chaotic systems. In general, the extreme sensitivity of chaotic devices makes it impossible to synchronize two separate systems, but Pecora found a way to do it in a simple electronic system. "One night, 3 o'clock in the morning, it hit me," says Pecora.

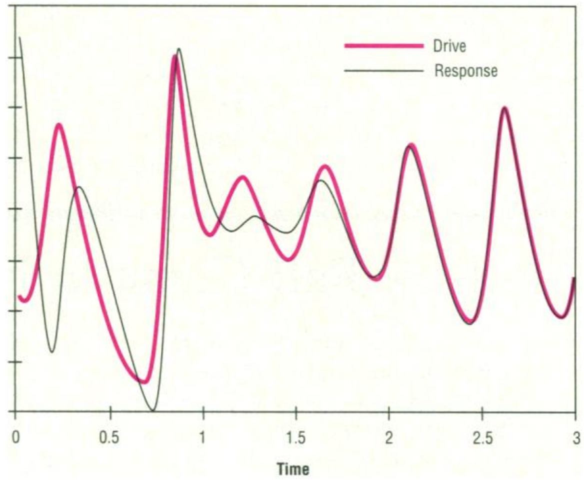
Pecora and Carroll constructed a circuit whose voltage fluctuates chaotically, then duplicated a part of this circuit to form a second subcircuit. Left alone, the voltages of both the complete circuit and the subcircuit fluctuate in ways that seem to be unrelated to each other. But when the researchers send a signal from the complete circuit to the subcircuit, mimicking the output just of the part of the circuit that wasn't duplicated, the outputs of both circuits will stay in sync. (This will happen, Pecora says, if the subcircuit satisfies certain mathematical parameters—technically speaking, it must have a negative Lyapunov exponent.)

Pecora thinks the scheme —which he first dreamed up a little more than a year ago and has been perfecting ever since—may be useful for various communications applications, particularly sending coded signals. Imagine two chaotic circuits set up in different parts of the world, one a partial duplicate of the other. First you synchronize the two devices with one chaotic signal. Then you send a second chaotic signal from some predetermined location on the first circuit to the partial circuit, superimposing a nonchaotic message onto the chaotic signal. To anyone else, the signal looks random. But since the partial circuit is in step with the main one, it could conceivably filter out the chaos and reveal the hidden message.

For both sets of Navy researchers, their ideas are often so new they aren't sure what to do with them. "Like the laser [when it was first introduced], it's a solution waiting for a problem," Carroll says.

A good example is Carroll and Pecora's latest experiment, which has not yet been published. In consumer electronics, a master signal is often used to coordinate the operation of several components. These devices are linear, and tend to stay synchronized. But what if scientists someday want to use nonlinear devices, which easily become unsynchronized? Pecora and Carroll have found that if they take a periodic, oscillating signal that is driving two nonlinear circuits, and electronically add a little bit of chaos to it, like magic, all the previously unsynchronized parts become synchronized again—and stay that way. Though Pecora isn't sure what the result may be used for, he notes that if there is chaos in the workings of the heart—as many suspect—his work may explain why: The chaos may actually prevent different parts of the heart from getting out of sync.

The Ditto and Pecora groups' experiments in controlling and directing chaos are perhaps the most far-reaching studies to date in this nascent field. But several other groups, including two last month, have reported success in suppressing, rather than directing, chaos in simple systems—in a fluid convection flow, and in a kind of magnetic behavior called spin-wave instabilities. And another group of researchers at the Naval Research Laboratory, headed by Sandeep Vohra and Frank Bucholtz, recently used nonlinear effects to improve the performance of a measuring instrument. By corralling a phenomenon called period doubling, which occurs at the transition from normal to chaotic motion, they improved the sensitivity of fiber-optic magnetometers, a common kind of magnetic field sensor. The enhancement allows fiber optic magnetometers to detect very low-frequency fields. They hope to publish their results soon.




**Chaos in sync.** *Chaotic outputs from two circuits fluctuate independently at first, but Lou Pecora's device quickly synchronizes them.*

Nobody expects major applications of controlled chaos anytime soon. One reason is that "you have to recalibrate your thinking from your old linear ways, to thinking in this new way," Pecora says. Another is that there are very few people studying the area. Besides the three Navy groups, there are

## Flying High With Chaos Control

When the Wright brothers made their pioneering flights, they adjusted the flow of air over the wings of their plane by pulling wires to change the shape of the cloth wings. This primitive mechanism seems a far cry from the hydraulically controlled ailerons and flaps planes use now to help them take off, turn, and land. Yet engineers at Grumman Corp. want to bring back the Wright brothers' concepts—with a twist. Instead of pulling wires, they want to apply the recently discovered method of controlling chaos.

Along with several other companies, Grumman has been trying to develop an adaptive wing—one that replaces the heavy, awkward hydraulics with "smart" materials, allowing the wing to react and adjust to fluctuating wind conditions and pilot commands by changing its shape. Such a system would have several advantages, says Gareth Knowles, a laboratory chief for controls and dynamics at Grumman: It would be much lighter, saving fuel; it would react "much, much faster" than traditional hydraulic controls, giving planes unprecedented maneuverability; and it would consume far less power.

Last fall, Knowles' team started investigating Terfenol-d, a metal composite that changes its length when exposed to magnetic fields. While Terfenol-d's ability to exert a large force made it promising, Knowles' team wasn't sure how to control the inherently nonlinear material. So, in January, when Knowles heard Bill Ditto speak on how to control the chaos in a magnetoelastic ribbon, he was excited: The new technique might give Grumman a way to manipulate the Terfenol-d.

Although it's still in an embryonic stage, Knowles' scheme would work something like this: When a pilot (or a computer) gives a command, instead of flaps going down or up, magnetic fields would fluctuate, altering the length of the Terfenol-d inside the wing. The Terfenol-d's movement would then be amplified and transferred to the wing itself.

Altogether Knowles speculates it would cost \$10 million to \$12 million to develop and build a one-third scale model. "Considering the payoff, that's like spitting in the ocean," he says. ■ **R.L.**

probably less than five other U.S. teams working directly on experimental applications of chaos to devices, and some of those actually are investigating phenomena related to chaos, rather than chaos itself. And it's no coincidence that most of the pioneering work is being done in Navy laboratories: Since 1983 the Office of Naval Research has been the only government agency with a funding program specifically for chaos studies.

There are, however, signs that interest in the field is growing. The Electrical Power Research Institute (EPRI) held a workshop on applications of chaos and complexity theory last November in which researchers from around the world discussed everything from chaos in conveyor belts, to controlling chaos, to chaos in chemical mixing. Since then Jong Kim, a director of exploratory research at EPRI, says he has been besieged by grant requests and proposals, and the organization is considering expanding its funding of chaos research.

Until now, almost all the work done in chaos has been theoretical or computational—especially modeling the complex behavior of the differential equations in which chaos was first discovered. Next October, however, all three Navy teams will host the first ever experimental chaos conference. Forty talks are expected, which suggests that the new results may be spurring a shift toward more experimental study of chaos.

"There's too much good stuff in here" for it not to catch on, Pecora says. "This field is going to be no different than quantum mechanics: Eventually...it's going to have a big [practical] impact." If Pecora has his way, it'll be sooner rather than later...but to ensure that his hopes come to fruition, he may have to find even more sophisticated methods of controlling chaos.

■ ROBERT LANGRETH

# A New Ball Game in Nuclear Physics

It's convenient to think of the atomic nucleus as a ball—a little lumpy, to be sure, but basically spherical. Nuclear physicists have known for decades, however, that highly excited or unstable nuclei momentarily stretch or bulge before they decay or settle back into a lower-energy state. And now researchers are exploring the behavior of nuclei that have been deformed more drastically. The quirky ways of these "superdeformed" nuclei are challenging some established ideas about nuclear structure.

The superdeformed nuclei now in the spotlight were discovered in 1986 by Peter Twin and his colleagues at the University of Liverpool. By using particle accelerators to smash together the nuclei of heavy elements, the researchers produced fused "compound" nuclei that sometimes emerged with wildly distorted—and curiously persistent—shapes. The spectrum of the gamma rays emitted by these nuclei in the aftermath of the collisions suggested that some of the nuclei had been flattened into the shape of a discus or stretched like a cigar, the Liverpool researchers reported.

These superdeformed nuclei turned out to be surprisingly long-lived, says nuclear physicist Witold Nazarewicz of the University of Warsaw, who is currently working at the Joint Institute on Heavy Ion Research at the Oak Ridge National Laboratory. Such nuclei might be expected to lose energy rapidly and settle back into a more spherical shape. But some of the distorted nuclei discovered by Twin and his colleagues tend to linger in the superdeformed state.

What keeps these nuclei squashed or stretched, Nazarewicz and his colleagues theorize, is a combination of classical effects such as garden-variety centrifugal force and quantum effects. The unimaginably fast rotation of a superdeformed nucleus—up to $10^{20}$ revolutions per second, says Nazarewicz—is part of the story, generating forces similar to but enormously greater than those that slightly flatten the spinning earth. Quantum effects, like those that shape the orbitals of electrons, also act to deform the nucleus. In the case of superdeformed nuclei, both types of forces reinforce each other. The stability that results from these two aligned forces gives researchers time to probe the properties of their odd nuclear specimens.

The latest mystery involving superdeformed nuclei came to light last year in an analysis of the signals they give off at the end of their brief lifetimes. Comparing the gamma rays emitted by superdeformed nuclei of different types as they lost energy and relaxed into ground state, a number of teams began seeing some eerie matches in the spectral fingerprints. This was a surprise because the gamma-ray fingerprints of different excited nuclei should be as dissimilar as the fingerprints from different people. Because nuclei emit gamma rays in order to lose rotational energy as they slow down from a fast-spinning excited state, the array of emitted energies should depend on the exact size and shape of the nucleus. Thus each type should emit a characteristic array—a unique signature.

Almost immediately, other nuclear physicists started exploring this new phenomenon, among them Marie-Anne Deleplanque of Lawrence Berkeley Laboratory. "What we've seen is totally unexpected," she says of the phenomenon, which is called band twinning.

Band twinning was first seen in superdeformed dysprosium-152 and terbium-151, which emit nearly identical spectra, but several isotopes of mercury and its nearest neighbors in the periodic table also show the same unexpected matches. "We have no reason to think [these nuclei] should do that," says Deleplanque. "They have different sizes, different moments of inertia....We have no explanation to account for it."

That didn't inhibit Deleplanque and other nuclear physicists from describing their first stabs at solving the puzzle at the American Physical Society (APS) meeting in Washington, D.C., last month. Nazarewicz, a theorist, suggested one possible explanation, based on a postulated quantum-mechanical property called pseudo-spin. Pseudo-spin might lead to correlations in the amount of angular momentum that nuclei of different types could gain or lose at a time. Because these steps determine the spacing between energy levels, and thus the wavelength of emitted gamma rays, pseudo-spin might account for some of the band twinning.

But pseudo-spin can't fully explain the striking energy matches observed, says Nazarewicz. The size of a nucleus—its actual diameter—as well as its angular momentum should affect its gamma spectrum. A difference of only one proton or neutron should be more than enough to distinguish the gamma emissions of two nuclei.

Nazarewicz told the APS gathering that he expects more twists to the story. He thinks the pairs of otherwise disparate deformed nuclei that show band twinning may be alike in some unsuspected way. "Band twinning shows there may be a new symmetry we don't know about," he says, a kind of symmetry hidden in ordinary nuclei.

■ FAYE FLAM