fluid into the fault. His model relies on the fact that at depths greater than about 15 kilometers, below the fault itself, heat and pressure make rock flow like putty rather than break. This ductile flow, says Rice, would tend to squeeze high-pressure fluids out of the rock at those depths and into the fault above. There the fluids would be confined by the relatively impermeable rock surrounding the fault until they leaked away and were replaced by more fluids pumped up from the ductile region. From their inspection of exhumed faults, Chester, James Evans of Utah State University, and Ronald Biegel of Columbia University's Lamont-Doherty Geological Observatory tend to favor Rice's model of flowing fluids rather than Byerlee's static version; they see mineral deposits in the form of veins—a strong indication of fluid flow.

The notion that faults might be wedged open by high-pressure fluids pumped in from below is a long way from the idea that the high friction of rock on rock makes faults strong. But if researchers can figure out where fluids get into faults and just how they weaken them, they may be able to rebuild their understanding of fault mechanics into a foundation for earthquake prediction. Knowing how the fluid-induced weakening varies along a fault, for example, could be crucial to forecasting the next damaging quake. And a picture of how fluids weaken faults might help seismologists understand how some faults—nearly horizontal ones such as those beneath the Basin and Range province of Nevada and Utah, for example—slip at all (*Science*, 3 June 1983, p. 1031).

But the new picture of weak faults may also help heal a rift—the intellectual rift between laboratory experimentalists, whose work on fault mechanics had seemed increasingly at odds with the behavior of real faults, and some of their colleagues doing the fieldwork that conflicts with the laboratory data. If invoking high fluid pressures can eliminate "the discrepancy between what we learn in the lab and what Nature does on a large scale," says Rice, "then it would mean lab mechanics would be useful for learning what the precursors might be" for the next big quake. Odd that peacemaking might emerge from such violence as Loma Prieta. ■ RICHARD A. KERR

ADDITIONAL READING

A. J. Michael, W. L. Ellsworth, D. H. Oppenheimer, "Coseismic stress changes induced by the 1989 Loma Prieta, California, Earthquake," *Geophys. Res. Letts.* **17**, 1441 (1990).

M. D. Zoback and G. C. Beroza, "Heterogeneous slip and stress release in the Loma Prieta earthquake II: Evidence for near frictionless faulting and complete coseismic stress drop," *EOS, Transactions, Am. Geophys. U.* **72**, 309 (1991).

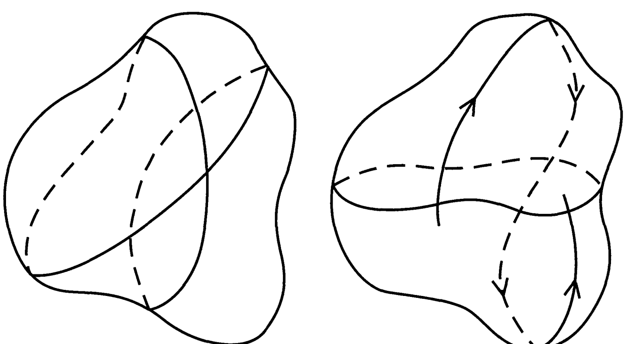
What Goes Around Comes Around

An unlikely partnership of two mathematicians has solved one old problem and suggested ways to solve many new ones

IF THERE IS AN ODD COUPLE IN MATHEMATICS, it would surely have to be a differential geometer hooking up with an expert in dynamical systems. One mainly studies the structure of stationary objects, while the other is interested primarily in change. Normally those two views of the world don't mix. But don't try telling that to John Franks and Victor Bangert.

Franks, an expert in dynamical systems at Northwestern University, and Bangert, a differential geometer at the University of Freiburg in Germany, recently teamed up to solve a problem that had vexed differential geometers for decades: How many closed geodesics are there for any Riemannian metric on a sphere—or, to put it differently, if Arnold Schwarzenegger crushes a basketball, how many unbroken rubber bands can Magic Johnson wrap around it?

The answer—that there are infinitely many conceptual rubber bands (closed geodesics) that can be wrapped around any distorted sphere—comes from an entirely new theorem Franks and Bangert developed, and it not only solves Magic's basketball puzzle, it is also pregnant with "offspring" from the marriage of mathematical disciplines that could have implications for a variety of scientific fields from plasma physics to new materials.


SOURCE: BARRY CIPRA

Distorted basketballs. *On a crushed sphere, some curves close up* (left), *while others may wrap around forever.*

The new theorem is especially good news for geometers, who consider closed geodesics worth their weight in gold. A geodesic, whether it's wandering about on the surface of a sphere or cruising through the gravitationally curved space-time of Einstein's theory of general relativity, is essentially just a curve that follows the curvature of whatever surface or space it lies in. "Following the curvature" means that geodesics have a "shortest path" property: Taken in segments, a geodesic connects points in the most direct way possible, just as a rubber band tries to make itself into as short a loop as possible. By analyzing the lengths of these loops, mathematicians can deduce many properties of the surface they lie on.

On an ordinary, undistorted sphere, the geodesics are all great circles, such as the earth's equator. And they are all "closed," meaning that traveling along one of them always brings you around the sphere, back to where you started. But on other surfaces—ones that Schwarzenegger has worked over, for example—geodesics are typically not closed. They are more like broken rubber bands stretched to an infinite length and wrapped endlessly around the surface. Looking for closed geodesics among this tangle of curves is a bit like searching for the proverbial needle in a haystack. But Bangert and Franks' result shows that there are infinitely many needles in this particular haystack.

To prove that there are an infinite number of closed geodesics for any closed surface, Bangert started with a single closed geodesic, which served as an equator. The only property an equator must have—aside from being closed—is that it not cross itself. For any geodesic that does cross the equator, one of two things must happen: Either it crosses the equator again, or it doesn't.

Several years ago, Bangert proved that if a geodesic crosses the equator, but afterward stays in one "hemisphere," then there are infinitely many other geodesics that are closed. He did this using classical techniques in differential geometry. But the other case, where each south-north crossing is followed by a north-south crossing, defied his geometer's bag of tricks.

So he turned to an approach first suggested by American mathematician George David Birkhoff in the 1920s. Birkhoff showed that each south-north crossing can be identified by two numbers, one to specify the position of the crossing (i.e., its "longitude") and one to specify the angle. Viewed as coordinates, these numbers describe a point in a washer-shaped region on a surface called an annulus. Following geodesics from one south-north crossing to the next can be interpreted as defining a mapping that sends the annulus onto itself. Such mappings are the bread and butter of dynamical systems. The theory of dynamical systems can be loosely described as the study of mappings that send a region back into itself repeatedly. In particular, are there points that come back to where they started?

For Bangert, the crucial feature of such periodic points is that they correspond precisely to closed geodesics. Clearly, Bangert needed a specialist in dynamical systems, and in a match that might have been made in Riemannian heaven, he found Franks.

"It was fairly clear what you needed to know" in order to finish the proof, Franks recalls. "It just wasn't so clear how to do it." Franks had previously proved numerous theorems related to the existence of periodic points, but none of them was quite enough as they stood to finish Bangert's argument. What was called for—and what Franks finally proved—was a new, more far-reaching theorem in dynamical systems.

Franks' new theorem says that for a particular class of annulus maps called area-preserving annulus maps, if there is one periodic point, then there are infinitely many. From there it's an easy step to deduce the existence of infinitely many closed geodesics.

Introducing new methods from dynamical systems to solve a problem in differential geometry "is very significant," according to Robert Molzon, program director for geometric analysis in the Division of Mathematical Sciences at the National Science Foundation. Molzon sees potential applications in "everything from general relativity and understanding the largescale structure of the universe, down to very smallscale problems such as boundaries between phases in materials science."

Franks is also optimistic about applications within dynamical systems. Among the real-world possibilities are the quandaries faced by physicists searching for plasma containment techniques for nuclear fusion. Fusion experiments generally take place in ring-shaped containers, so here come the annulus maps. It would be only fitting if this unlikely marriage of mathematical disciplines gave rise to an even more unlikely solution of the world's energy problems by showing that it's possible to wrap infinitely many rubber bands around a misshapen globe. ■ BARRY CIPRA

Drawing a Bead on Superdense Data Storage

Researchers dream of writing data on small groups of molecules. One strategy: Lock the molecules in plastic beads

IN COMPUTER MEMORIES, DENSER IS BETTER. Most researchers have been striving to cram more data into a smaller space by shrinking the patches of magnetic or optical storage medium needed to record single bits of information. But a few researchers have been questing after an optical memory that would achieve densities thousands of times greater by stacking many bits of data on the same small patch of storage medium.

The key, they've long understood, would be to use laser light at various frequencies to record bits of data on actual molecules within the patch. The trouble is that at room temperature, molecules can absorb light at a broad range of frequencies, so writing a bit at one frequency might blot out a bit written at another frequency. The only obvious way to stabilize the molecules so that they respond to specific frequencies has been to cool them to the temperature of liquid nitrogen, a prohibitively costly proposition for an everyday computer memory. But physicist Stephen Arnold of New York's Polytechnic University thinks he has a better way.

Arnold's solution to this high-tech conundrum, which he will summarize at the American Physical Society meeting in Indianapolis this month, lies in little beads of cheap polystyrene. Just microns across, these tiny beads have a remarkable ability to ensnare photons from a passing beam of laser light, Arnold says. What's more, the beads tend to absorb and emit light only at razor-sharp frequencies, forcing molecules trapped within them to respond at exactly the same sharp frequencies whatever the temperature. Arnold's work, says IBM's W.E. Moerner, a prominent figure in the search for molecular memories, "is one of the most interesting things that have happened in the field."

Arnold, a specialist in the properties of tiny beads of liquids, semiconductors, and other substances, got the first hint of the phenomenon he now hopes to exploit in 1985, when he beamed laser light at a glycerin droplet a few microns wide filled with fluorescent dye. "When we tuned [the laser] to the right wavelength, we detected these enormous bursts of light," he recalls—20 times more than the droplets' normal fluorescence.

Clearly, the dye molecules were capturing and then reemitting far more photons from the laser than they normally would. They had to be doing so with the help of the glycerin droplets, and a clue to the role the droplets might be playing came from Arnold's discovery that the size of the spheres was critical.

Spheres a fraction of an angstrom smaller or larger than the one that had fluoresced refused to respond to the same frequency of light—but they would react to a slightly different frequency. To Arnold, the pattern suggested that when the size of the sphere and the frequency of the light were matched just right, the light was getting trapped. That was a surprise: Ordinarily, a photon of light that makes its way into a transparent sphere pops out again after bouncing around the interior a couple of times. But Arnold realized that, given the right combination of size and frequency, the photon's wave was getting locked in a resonance—a standing wave, rather like a sound wave in an organ pipe or the wave associated with an electron orbiting an atomic nucleus.

As a result of the resonance, photons were skipping around just inside the spheres for a few hundred thousand orbits before finally leaking out. And having that good a shot at a photon was too much for the dye molecules to resist: They absorbed and then spat out far more photons than usual, accounting for the burst of fluorescence at the resonant frequency.

Arnold didn't have any particular applications in mind for these "photonic atoms," as he calls the photon-nabbing microparticles. But he went on studying them just the same, discovering along the way that solid, microscopic beads made of polystyrene have the same photon-trapping ability as the glycerin droplets. And in 1990, he presented his work at IBM's Almaden Research Center in San Jose, California, where he learned something new. There Moerner and his group, like many other researchers around the world, were trying to perfect "spectral hole-burning"—the technique that might lead to a superdense molecular memory.

In hole-burning, tuned laser light is