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.

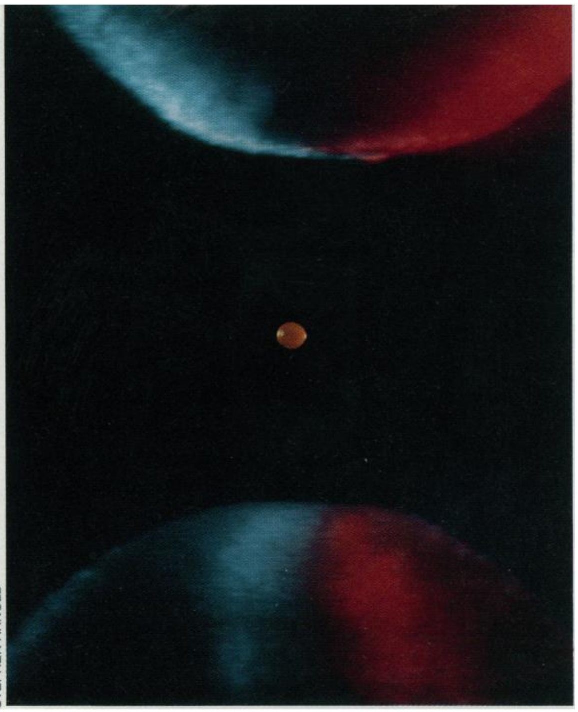
Clearly, the dye molecules were capturing and then reemitting far more photons from the laser than they normally would. They had to be doing so with the help of the glycerin droplets, and a clue to the role the droplets might be playing came from Arnold's discovery that the size of the spheres was critical.

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



STEPHEN ARNOLD

Point of light. *Micron-sized spheres—in this case a glycerin droplet suspended between electrodes—can ensnare light waves.*

shined on a transparent solid riddled with light-absorbing impurity molecules. When the laser is tuned to a frequency absorbed by some of the impurities and its intensity is cranked up, the light-absorbing impurities can be excited until some of their molecular bonds are broken or they give up electrons. The disrupted molecules can no longer absorb light at that frequency, creating a "spectral hole" where there is almost no absorption—a hole that can later be "read" with a low-intensity laser.

Best of all, because each patch contains impurities that absorb at many different frequencies, several holes, each at its own frequency, can be written onto the same patch, each hole potentially representing a "0" or "1" in a computer memory. As a result, such a memory could offer densities tens of thousands of times greater than conventional optical disks. The catch is that the frequencies of the holes would broaden and overlap one another at temperatures above that of liquid nitrogen—77 degrees Kelvin.

But Arnold's Almaden visit got him thinking. His photonic atoms responded to the same frequencies no matter what the temperature, and a collection of randomly sized spheres would certainly provide the broad array of different frequencies needed for a stacked memory. Though there was no good way to assemble dye-laden glycerin droplets into a memory, the polystyrene beads would do the trick, if they could somehow be combined with molecules that could be altered by laser light.

Working with William Whitten and Michael Ramsey at Oak Ridge National Laboratory, Arnold decided to imitate the original glycerin droplets by embedding fluorescent dye molecules in the plastic spheres. The dye should fluoresce at the spheres' size-dependent resonant frequencies, and a high-intensity laser could destroy the fluorescence to burn a hole at any one of those frequencies. To test the scheme, Whitten and Ramsey soaked an assortment of different-sized beads in dye, placed them in water on a glass slide, and beamed a low-intensity laser at them at a range of different frequencies. As hoped, the beads fluoresced at such a wide variety of frequencies that the spectrum was essentially flat. Then Whitten and Ramsey turned up the intensity at one frequency to try and write a spot on the sample. When they came back with the low-intensity "read" laser, they found the sample no longer fluoresced at that frequency; they had indeed burned in a hole. Arnold later repeated the experiment, using various frequencies to create multiple holes.

All that has made Arnold optimistic that the beads could form the basis of a practical hole-burning memory, in which multiple bits of data could be written on the same small cluster of beads. Moerner, too, is intrigued by the possibilities, though he is quick to point out a problem. The beads, he notes, are thousands of times bigger than molecules, which might eliminate the density advantage of a hole-burning memory. "Arnold's work is new, and we have to see if the [density] problem can be solved," he says. Besides, he adds, the competition just got tougher: a Swiss team recently claimed some success at getting a specially doped crystal to retain spectral holes at room temperature.

Arnold concedes his beads are a long shot for commercial memories. But he notes that even though the beads are big by molecular standards, they would still have a hefty density advantage over conventional memories if they were packed in a three-dimensional array. In any case, Moerner and other researchers agree that, memory or no, Arnold's spheres make for some interesting physics—a physics that might center on a new sort of artificial matter. "Photonic atoms may turn out to be able, in effect, to exchange photons," Arnold says, much as atoms in a compound exchange electrons. "We're only just starting to look at this question, but if they do we'd consider them to be photonic molecules." Could the next hot field be photonic chemistry? ■ DAVID H. FREEDMAN

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Antigen Processing:

Immunologists have long known that the immune system must recognize an invading organism from portions of its proteins before it can destroy the invader, but one key question in immunology has been: How do cells chop up foreign proteins from intracellular invaders like viruses and present them to the immune system? The mechanism used by cells for degrading and presenting proteins has become a field of its own, known as antigen processing, that is one of the fastest-moving in all of science today. Indeed, antigen processing studies have moved so fast that if you had asked insiders for a status report only a few weeks ago, they would have told you that researchers were putting the finishing touches on their picture of the biochemical pathway by which antigens are processed. Ah, but that was then, and now another group has come up with an alternate—and unexpected—pathway.

Behind this revisionism are Donald Hunt, Victor Engelhard, and colleagues at the University of Virginia School of Medicine in Charlottesville, along with collaborators Kazuyasu Sakaguchi and Ettore Appella at the National Cancer Institute in Bethesda, Maryland. Referring to their paper on page 1264 of this issue of *Science*, Jonathan Yewdell, a specialist in antigen processing at the National Institutes of Health, says: "Now it appears that there are two ways of feeding [protein fragments] into the system."

And while, for the moment, this new information remains primarily a matter of basic research, knowledgeable immunologists believe that it could ultimately have important clinical implications. "The hope," says David Margulies of NIH, "has always been that by understanding what [protein fragments] are presented to the immune system, we might have a better understanding of the etiology of diseases and be in a better position to design drugs to modulate [the] immune response." So, the more knowledge the merrier—even if it upsets prior conceptions.

The "old" path to antigen processing begins after infection, when viral proteins from the cell's cytoplasm are chopped up into fragments called peptides by a ball of degradative enzymes known as the low-molecular mass polypeptide (LMP) complex. The peptides are then transferred into the endoplasmic reticulum (ER), a membranous compartment in the cell that serves as a conduit for newly synthesized proteins to reach the cell surface. But the peptides can't get into the ER on their own; to cross the lipid membrane that bounds the compart-