PHYSICS

Gentle Force of Entropy Bridges Disciplines

Anyone who has tried to reunite two socks after a tumble in the dryer is well acquainted with entropy. Over time the universe slides on a one-way course toward disorder. Cream mixes irretrievably into coffee. Our bodies lose heat to the cold winter air. But sometimes, it turns out, entropy can be a force for organization. Under certain conditions, the clothes dryer will, in effect, pair up socks.

Physicists have recently rediscovered this strange phenomenon, in which an increase in entropy in one part of a system forces another part into greater order. Now their enthusiasm is spreading. Engineers are awakening to the possibility of harnessing the force of entropy to build ordered structures. And a recent paper in *Physical Review Letters* showing how this ordering force can push on membranes has rekindled speculation that living cells might take advantage of this little-known trick of physics. The idea is "exquisitely interesting," says Adam Simon, a biophysicist at Merck & Co., Inc., in West Point, Pennsylvania. "If entropic forces are playing a role, that's a complete rethinking" of what goes on in a cell.

The idea that entropy could tidy up as well as tear down actually goes back to a 1958 paper by two Japanese physicists. They described how two large particles in a sea of smaller ones would eventually find each other and stick together. By snuggling close together, the two freed up a little bit of space for the smaller particles to bang around in, increasing the overall disorder.

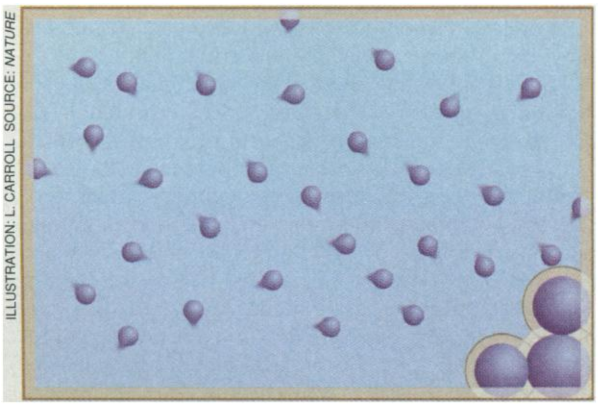
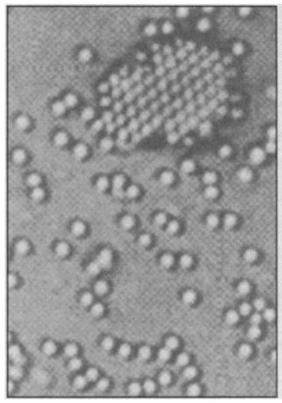


ILLUSTRATION: L. CARROLL SOURCE: NATURE

Making space. Big spheres can make more space for little ones by clustering together or moving into a corner. That's because large spheres and container walls are edged by a forbidden area (brown) where a small sphere cannot fit.

The revival began in a drop of water at the University of Pennsylvania in 1992. Peter Kaplan, then a graduate student there, had been mixing up a colloid cocktail. He let loose two sizes of microscopic plastic spheres in a bit of salty water. Instead of a uniformly murky solution, Kaplan saw small structures forming around the edge of the container. The larger spheres were packing themselves into tightly ordered crystals. It was like watching cream unstir itself from coffee, or a movie of erosion run backward.

After a bit of head scratching, Kaplan, his adviser Arjun Yodh, and colleagues realized that they were seeing a strange side of entropy. The large spheres were crowding toward the edge of the drop to make more room for the small spheres to be disorderly, just as people waiting out a dance number in a discotheque crowd against the walls to make more room on the dance floor. Because each sphere contributes equally to the overall entropy, the increase in entropy from the many small spheres more than compensated for the reduction in entropy from the few large ones.



DINSMORE ET AL., EUROPHYSICS LETTERS

Up against a wall. Micrometer-sized spheres in water are forced into crystalline order on a glass wall when smaller spheres are added.

The force of entropy acts through the uncoordinated movements of the smaller spheres. "You can literally watch it happen under a microscope," Yodh says. The researchers made videos and saw that the random bombardments of the small spheres would eventually bring a big one near to the wall, where it would stick, pelted on its exposed sides by the smaller beads. Then the big spheres would pile up one by one. It takes a certain density of small spheres to trigger the pileup, says Yodh. Add a bit more water, "and [the crystal] just melts."

Now Yodh and his colleagues have taken the work another step further. In a paper in the 12 January issue of *Physical Review Letters*, they showed that, in an arterylike tube filled with small and large spheres, entropy will nudge the large spheres to the edge of the tube, and then toward the place where the tube bends the most. "In a microscope it looks very magical," says Anthony Dinsmore, one of the authors, who is now at the Naval Research Lab in Washington, D.C. Actually, he explains, the big spheres are just surrounding themselves with as much wall as possible to make more room for the little ones.

Dinsmore adds that if the wall is flexible, the large spheres should embed themselves in it. That would completely take them out of the picture and maximize the entropy. And that, says Dennis Discher, a biologist at the University of Pennsylvania, just might explain the mysterious process in which the nucleus of a red blood cell precursor buds off and is shed before the cell heads out into the bloodstream as a sack of hemoglobin. Maybe the nucleus, like a large ball, gets shoved out when enough hemoglobin—which plays the role of the small spheres—builds up inside the cell.

As Simon notes, the conditions in a cell are just right for entropic forces to get a foothold. Cell fluids are salty, which would tend to screen out the much stronger electrostatic forces that could overwhelm entropy's gentle influence. And, he says, there are plenty of proteins and other objects floating around that could play the role of the small spheres. Indeed, biochemists Steve Zimmerman and Allen Minton at the National Institutes of Health anticipated some of the current speculation by showing in the 1980s that DNA ligation—which stitches DNA strands together—can proceed 10 times faster in vitro when tiny molecules are added to the mix. "It's a whole different kind of chemistry going on" when things get crowded, Minton says.

Engineers now hope to harness this force for their own purpose: developing crystals that reflect visible light perfectly at all angles. These long-sought "photonic band gap" materials—ordered arrays of particles spaced about a wavelength of light apart—could improve lasers or keep fiber-optic cables from leaking light when bent into a sharp U-turn, says David Pine of the University of California, Santa Barbara. But scientists have had trouble getting the tiny spheres to arrange themselves in the right crystal structure.

Pine hopes a simpler method may work: Lay down a regular network of ridges on a sheet, then use the entropic force to nestle metal spheres into the ridges. These spheres would form the first layer of the crystal, which would provide a template for subsequent layers. The only problem, he says, is making the pattern of ridges with the necessary 0.5-micrometer accuracy. Still, he says, the entropic force is ideal. "You can control its strength by adjusting the size and concentration of spheres," he says. If Pine is right, he'll have made an ordered niche in an increasingly disordered world.

–David Kestenbaum