In this section of* Resonance, *we invite readers to pose questions likely to be raised in a classroom situation. We may suggest strategies for dealing with them, or invite responses, or both. "Classroom" is equally a forum for raising broader issues and sharing personal experiences and viewpoints on matters related to teaching and learning science.

Order Out of Disorder

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Entropy, the extent of disorder in a physical system, is a concept which is central to physics. Paradoxically enough, entropic considerations can drive systems to ordered states. There has been a lot of interest in entropy driven ordering recently.

Here I confine myself to the simplest possible example to bring out the essence of the physics behind the formation of such ordered structures. Consider a container with a mixture of large (radius R) and small (radius a) balls suspended in a medium. Suppose that the densities of both kinds of balls are the same as the surrounding medium, so that gravitational effects are not at work. We also suppose that the balls are hard spheres so that they cannot penetrate one another. If such a container is shaken one finds that the balls will separate into two groups one consisting of large spheres and the other of small ones. The system orders itself! (This experiment has been done with polystyrene spheres of two sizes suspended in water.) How does one understand the result of this experiment?

Let us consider two large spheres and many small spheres in a container (*Figure 1*). Because of thermal fluctuations the spheres will continually move about and try to fill up as much volume as

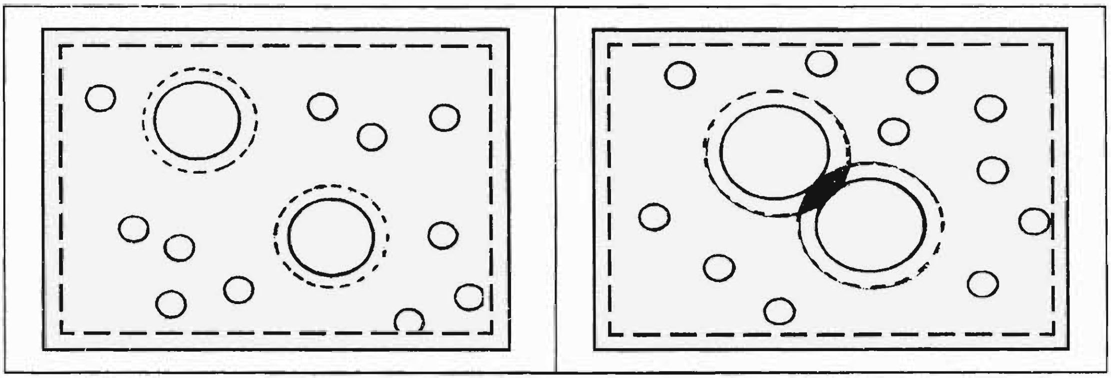

Figure 1 (left). Two large spheres and many small spheres in a container.
Figure 2 (right). Two large spheres touching each other. This leads to an overlap (black region) of excluded volumes giving the small spheres more space to wander around compared to the configuration shown in Figure 1.

is available to them. Since the small spheres are so much more numerous than the large ones, maximizing the entropy of the system essentially means maximizing the volume available to the small spheres. Let us consider the large spheres as temporarily fixed and estimate the volume available to the small spheres for given positions of the large spheres. In *Figure 1*, due to hard core repulsion, the centers of mass of the small spheres are excluded from the hatched regions: the centers of the small spheres cannot be within a distance a of the walls of the container or the large spheres. Now let us see what happens when the two large spheres approach each other (see *Figure 2*). One finds that the total volume available to the small spheres increases by an amount equal to the overlap of excluded volumes (indicated by the black region in *Figure 2*). Therefore, the total entropy of the mixture in *Figure 2* increases relative to the configuration in *Figure 1* by an amount proportional to the volume of the dark region. This increase in entropy gives rise to a net attraction between the large spheres. Interestingly, even though we have only hard core repulsions in the system, maximizing the entropy of the binary mixture gives rise to a net attraction between the large spheres leading to an ordered structure with large spheres segregated from the small ones.

By using the same guiding principle of maximizing the overlap of excluded volumes one can convince oneself that the least entropically favourable situation is the one shown in *Figure 3a* and the most entropically favourable one is the one shown in

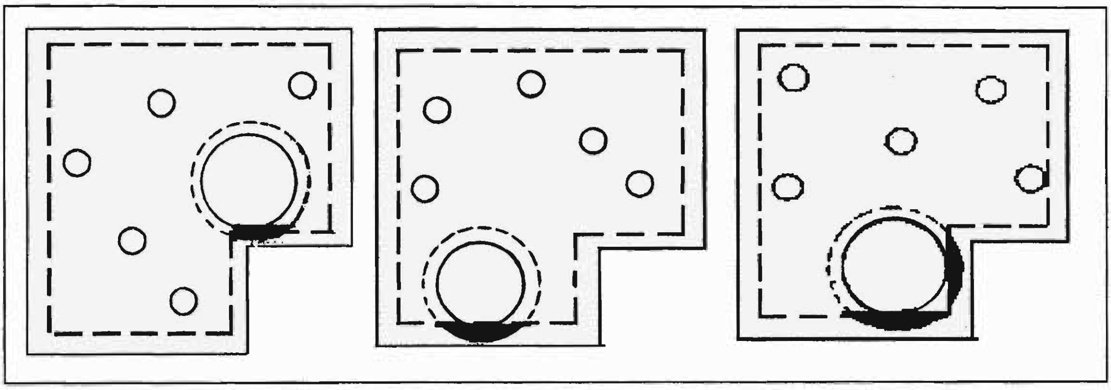

Figure 3c. Figures 3a – 3c are arranged in order of increasing entropy. The large spheres avoid a step (*Figure 3a*) and prefer to be in corners (*Figure 3c*). The forces which drive these particles to these preferred locations are entirely due to entropy. The forces are very small (10^{-14} Newtons), but quite adequate to enable the experimenter to manipulate the large spheres into organised arrays.

Figure 3(a–c).These three figures are arranged in order of increasing space available to the small spheres to wander around. Notice that the overlap (black region) of excluded volumes is the largest in Figure 3c and the smallest in Figure 3a.

From the band theory of electrons we know that the dispersion spectra of electrons exhibit band gaps.[1] Such band gaps are a consequence of the periodicity of the crystal in which the electrons move about. Similarly, a three dimensional periodic structure of large polysterene spheres can exhibit a photonic band gap (i. e. a frequency band over which light does not propagate through the material). Such an insulator of light would play a crucial role in separating channels of light propagation in optical computers which use light signals instead of electronic ones (See *Box 1*).

[1] These are intervals of energy in which the electron is unable to travel through the crystal.

In fact, Yablonovitch (at Bell Laboratories) has already succeeded in producing insulators for microwave radiation. The structures involved in such microwave insulators are a few centimeters in size and are easily machined. In contrast, a light insulator would be made up of structures of the order of a micron since the wavelength of light is much smaller than the wavelength of microwave radiation. It is not very easy to generate such minute structures. This is where entropy driven ordering comes in.

Box 1. Optical Computing

The father of modern computing machines was Charles Babbage (1792–1871) who had the idea of realising logic by means of mechanical elements. While Babbage was completely right in principle, mechanical computers are clumsy, slow and not at all practical. Babbage's idea had to wait for the development of electronics in order to become a reality. Electronic computers are fast because electronic signals can change faster than mechanical ones. The faster the computers are, more the complex calculations they can perform in a given time. Our ability to predict weather, for example, depends on the speed of our computers. There has been much interest in optical computing, which uses light signals rather than electronic ones. This replacement of electrons by light has already taken place in telecommunications. Optical fibres are far superior to telephone wires in their information carrying capacity. Before optical computers can become a reality, a number of technological problems have to be solved. We must have analogues of the components that appear in electronic circuits: conductors, insulators, transistors etc. Only then can we manipulate the optical signals and use them to perform computations. The tiny entropic forces discussed in the text may one day be used to make optical insulators.

One can make use of the delicate effects discussed here to engineer highly ordered particle arrays which can act as photonic insulators. Such materials are essential for building optical computers. Optical computing, therefore may not remain a dream for long!

Suggested Reading

[1] A D Dinsmore, D T Wong, Philip Wilson and A G Yodh, *Physical Review Letters*. 80. 409, 1998.

[2] S Sanyal, N Easwar, S Ramaswamy and A K Sood. *Europhysics Letters*. 18. 107, 1992.

[3] A D Dinsmore, A G Yodh and D J Pine, *Nature*. 383. 259, 1996.

[4] K A Suresh and G S Ranganath. *Current Science*. 66. 101, 1994 and references therein.

It is a truth very certain that, when it is not in our power to determine what is true, we ought to follow what is most probable.

Descartes