

Nonlinear dynamics

Jamming is not just cool any more

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All around us, things seem to be getting jammed. We travel on a highway and we are caught in traffic jams. At the wholefoods counter, grains and beans jam as they refuse to flow out of the bottom of the hopper into our bags. In factories, powdered raw materials clog the conduits that were designed to carry them smoothly. Our recourse in all these situations is to pound on our conduits, hoppers and dashboards until the jam miraculously disappears. We are usually so irritated that we have not really noticed that the jammed state, in all of these situations, has common properties. For example, the vibrations from the pounding actually do some good in reinitiating flow — except in the case of the traffic jam. Does the jammed solid then have different properties from the solids we normally encounter in the laboratory?

Writing in *Physical Review Letters*, Cates, Wittmer, Bouchaud and Claudin¹ contend that these jammed systems really belong to a new class of materials: 'fragile matter'. These systems resemble solids because the particles are driven into a jammed state by an externally applied stress. When jammed, the disordered system is caught in a small region of phase space with no possibility of escape.

Cates *et al.* propose that jammed systems are fundamentally different from ordinary solids in that, if the direction of the applied stress changes even by a small amount, then the jam will break up. A canonical example is a pile of sand, which appears solid: the upper surface slopes and sustains its shape despite the force of gravity, which one would expect to level the pile. But if one tilts or vibrates the pile, the grains shift and the solid melts. The authors argue that the unusual mechanical properties of fragile matter require a new theoretical description, which they first applied to a heap created by pouring sand onto the apex of a pile^{2,3}.

Traditionally, the forces within such a pile have been described using continuum elastoplastic theories. These are similar to models that describe ordinary solids⁴: every increment of stress in the material is related to a corresponding deformation, or strain⁵. The approach of Cates *et al.* is to start from a pile of completely non-deformable particles, for which strain is not an obviously useful variable. Their simple model of a chain of hard particles insists that the jammed system cannot be considered as an elastic body. Although it can support a large applied load in the same direction as the original jamming forces, the chain will fall apart if even an infinitesimal force is applied in a different direction. For an extended material such as a

sandpile, the material is fragile in the sense that a slight change in direction of the applied stress will change the entire structure of the force chains that give the pile its rigidity. Because there is no obvious relation connecting stress to strain throughout the pile, Cates *et al.* bypass the strain altogether and propose a relation between different components of the stress tensor^{2,3}. This continues to be a hotly debated assumption^{4,6–8}.

Cates *et al.* suggest that one way to reconcile the two approaches is to allow the particles to deform, so that the material can respond elastically to sufficiently small loads. One example of a system that is jammed and yet not fragile is foam. Shaving foam, for example, is jammed because the bubbles are tightly packed together under an isotropic stress, namely atmospheric pressure. If it were fragile, it would respond plastically to a shear stress, no matter how small. However, because bubbles deform, foam actually responds elastically as long as the stress is below a threshold value. Sand grains also deform slightly. Hence, for real systems, a continuum elastic description will always be useful. However, the new concept of fragile matter brings a valuable perspective from the opposite limit of completely non-deformable particles.

We would like to point out that the class of jammed materials may actually be broader than the authors suggest. They consider jamming only in systems with no attractive interactions (where the particle dynamics are constrained through an applied stress) and where the individual particles are large

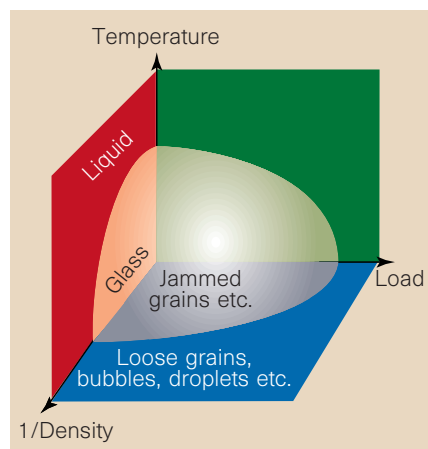


Figure 1 A possible phase diagram for jamming. The jammed region, near the origin, is enclosed by the depicted surface. The line in the temperature–load plane is speculative, and indicates how the yield stress might vary for jammed systems in which there is thermal motion.

so that there is no thermal motion. These two constraints may not be essential.

We know from studies of liquids and glasses that a system with attractive interactions often behaves in the same way as another that has only repulsive forces but is confined in a container (that constrains its density). In the case of jamming, the opposite situation may be possible: that is, one might be able to replace the constraints of an external pressure or stress with an attractive interaction between the particles. Thus, a supercooled liquid can be jammed into a glass simply by lowering the temperature, not by applying a stress. When a liquid is cooled below its freezing point, its viscosity increases rapidly. Eventually, it falls out of equilibrium into a disordered solid, or glass, where it only explores a small part of phase space, just as in the case of a jammed granular material or foam.

So might the concept of jamming and fragility include microscopic systems with attractive interactions, which unjam as one raises the temperature, as well as stressed macroscopic systems with repulsive interactions, which unjam as one applies an incompatible stress? We have sketched a speculative phase diagram for jamming (Fig. 1) that ties the different systems together. This phase diagram depends on temperature, load and density.

According to this picture, jamming can occur only when the density is high enough. One can then unjam the system either by raising temperature or by applying a stress. The phase diagram raises some interesting questions: for example, a glass may have a lower glass transition temperature under high shear stress. Likewise, a jammed granular material or foam may have a lower yield stress when random motions (that is, thermal fluctuations) are present. This would explain the beneficial role of banging on jammed conduits on the factory floor.

Whether jammed systems indeed share features that can be described by a phase diagram is an open question, but if our speculation has any merit it would bring together several different types of behaviour under one rubric. Are the dynamics of different systems approaching the jammed state also similar? If temperature and applied stress play similar roles in unjamming systems, is it possible that driven, macroscopic, athermal systems like granular materials and foams might be described in terms of an effective temperature? Is statistical mechanics useful at all in describing these systems? These and related questions will take years to resolve, but the picture of Cates *et al.* helps to point out some of the interesting conceptual problems that need to be addressed. □

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