Nonlinear dynamics

Jamming is not just cool any more

Andrea J. Liu and Sidney R. Nagel

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 Claudin[1] 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 solids[4]: every increment of stress in the material is related to a corresponding deformation, or strain[5]. 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
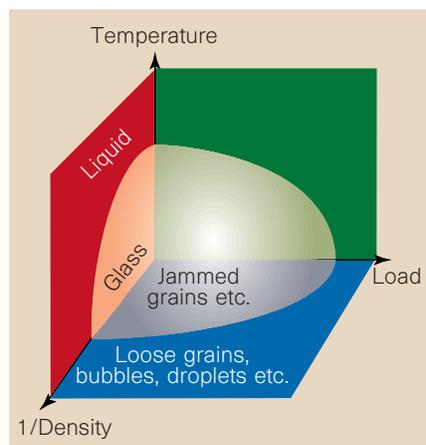
so that there is no thermal motion. These two constraints may not be essential.

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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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.**

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Biodiversity
Plants on the web

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What are the mechanisms that determine species composition in plant communities? In a world in which biodiversity decreases daily, the question is self-evidently important. One factor known to be central to the performance of individual plants, their interactions with each other, and even the species composition of the community itself, is the activity of mycorrhizal fungi, which are symbiotically associated with the roots of most land plants[1]. Until now, however, most experiments designed to investigate these effects have employed either single[2] or undefined mixtures[3] of fungal species, so their causes remain unclear.

A breakthrough comes with the study of van der Heijden *et al.* on page 69 of this issue[4]. Using field plots and mesocosms, the authors show first that the floristic diversity of two characteristically species-rich grass-lands, one representative of calcareous habitats in Europe and the other of abandoned fields in North America, depends upon the presence of a species-rich assemblage of fungal symbionts in the soil. They then propose a mechanistic basis for the observed effect.

The importance of mycorrhizal fungi for nutrient acquisition by individual plants has been known for some time[1]. But only recently have we become aware that because access to nutrients is increasingly restricted under competitive circumstances, mycorrhizal fungi can in part determine the outcome of interactions between plants, even to the extent of influencing the species composition of the community itself[3]. Emphasis upon the response of the plant has, however, left us with uncertainty about how the fungal partners bring about these changes. The unique feature of the work reported by van der Heijden *et al.* is that they have manipu-lated the composition of the fungal population, and have observed the effects on communities of plant species representative of those normally found in these types of grassland.

When four different species of mycorrhizal fungi were added, either individually or in combination, to reconstructed calcareous grassland communities, it was observed that different fungal species promoted different plant hosts. The outcome was that alteration of the composition of the fungal taxa produced statistically significant changes in the structure and composition of the plant community. From such observations it can be hypothesized that, because of the additive beneficial effect of each single fungal species, plant biodiversity, and ecosystem productivity, will increase with numbers of fungal symbionts (Fig. 1).

Perhaps the most novel of all the experimental manipulations undertaken by the group involved a test of this hypothesis using the abandoned-field communities. Ecologists have long been interested in the factors determining plant species composition in these systems[5]. Here, instead of adding different fungal taxa to each of the standardized plant communities, 0 to 14 fungal species were added per treatment. As the number of fungal species per system was increased, the collective biomass of shoots and roots rose — as, most importantly, did the species diversity of the plant community.

What are the functional and mechanistic bases of these effects? The differential effects of specific plant–fungus combinations on growth of plant species may, as the authors suggest, provide one functional explanation, particularly as benefits to the plant would be expected to provide positive feedback to the fungal partner.

Differences in functional compatibility between plant and fungal species certainly appear to be at the heart of the observed effect. Similar differences have been reported previously but in laboratory studies of single plant–fungus combinations[6]. In these, the effects have been shown to be caused by fungus-specific differences in the ability to supply phosphorus to the plant.

However, the situation in nature is far more complex. Mycorrhizal fungi can enter the roots of most plant species. The outcome is not only that almost all plants in the community are simultaneously colonized by several species of mycorrhizal fungi, but also that they are interconnected by the external hyphal network of these fungi which forms a web extending from the root surface into the soil. Greater functional compatibility in nature must therefore arise when one fungus amongst a group occupying the root system enables one particular plant species to perform better than the others (Fig. 1). This could be facilitated by greater rates of phosphorus capture and transfer, by production
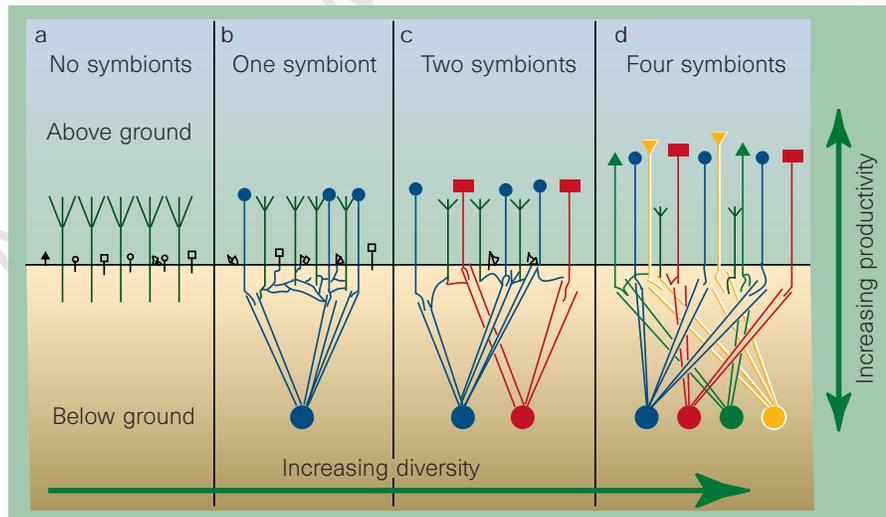

Figure 1 **Possible basis for the effects of fungal species richness upon plant biodiversity and production observed by van der Heijden *et al.*[4]. Although most plant species are susceptible to colonization by mycorrhizal fungi, so becoming incorporated into a below-ground mycelial web, some of these fungi induce more positive responses in one plant species than in another. Because of these differences in functional compatibility, addition of new fungal species (here shown only up to four) leads to increases in survival and vigour of a progressively larger number of plant species. In the absence of symbionts (a), species that are relatively unresponsive to mycorrhizal fungi (grasses, for example) dominate. Addition of a fungal species, and then increase in their number (b–d) enables progressively more of the highly responsive herb species to develop, at the expense of the grasses. Positive feedback to the increasingly diverse fungal population may lead to greater vigour of the fungal web, so contributing to more effective exploitation of soil resources and greater overall productivity.**