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Self-assembly and the Formation of Structure in Granular Materials[1]

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Particle systems self-assemble in ways that are sensitive to their environments. Proteins fold, polymers crosslink, and molecular systems form crystals. Granular materials, unlike proteins, polymers or molecules, are not sensitive to temperature, and will only form new structures when they are driven. This raises the question of how a granular state depends on the preparation protocol, and an even more basic question of what is needed to specify a granular state. I will focus on granular systems near jamming, where key state variables include the density and stresses. Systems of frictionless grains follow the Liu-Nagel[1] scenario of jamming, with a lowest packing fraction, ϕ_J, such that any system with $\phi < \phi_J$ is unjammed, and all isotopic states (shear stress $\tau = 0$) are jammed for $\phi > \phi_J$. For frictional grains the picture changes. For a given ϕ in the range $\phi_S < \phi < \phi_J$, it is possible to have stress-free (unjammed) states, highly anisotropic fragile states, and robustly jammed states. The fragile and strongly jammed states form spontaneously in response to shear. By inference, ϕ is not a state variable, but recent experiments[2] indicate that the non-rattler fraction, f_{NR} is. In $\phi_S < \phi < \phi_J$, the system response is inherently non-linear; under cyclic shear, the system self-organizes to new steady states via a process that resembles thermal activation, with shear stress replacing energy[3]. The activation is provided by shear strain. We observe similar relaxation under cyclic compression. An important question is, what is (are) the organizing principle(s) which govern jamming by shear, and systematic reorganization under cyclic driving. 1Liu, A. & S. Nagel, Nature 396, 21 (1998). 2D. Bi et al., Nature 480, 355 (2011). 3 J. Ren et al. Phys. Rev. Lett. **110**, 018302 (2013)

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