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Precisely cyclic sand: self-organization of periodically sheared frictional grains

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Using molecular dynamics (MD) simulations, we show that cyclic shear of a granular material leads to dynamic self-organization into several phases with different spatial and temporal order. We present a phase diagram in strain − friction space which shows chaotic dispersion, crystal formation, vortex patterns and most unusually a disordered phase in which each particle precisely retraces its unique path. However the system is not reversible. Rather the trajectory of each particle, and the entire frictional, many-degree-of-freedom system, organizes itself into a limit cycle absorbing state. Surprisingly, the cyclic states remain spatially disordered while the ordered states are chaotic.