QUICK STUDY

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When dense crowds act like soft solids

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Although mass gatherings of people are normally safe, sometimes their physical interactions prevail over social norms and peaceful events can become disasters.

On a late June afternoon in 2017, one of us (Bottinelli) was passing by San Carlo Square in Turin, Italy. It was a warm, beautiful day with a festive vibe as people gathered to watch a soccer championship final on a large screen. Around 10:00pm, a loud bang—perhaps a fire cracker exploding or a security barrier falling over—startled several people and triggered a stampede. The festive summer night turned tragic, with some 1500 people injured and two fatally trampled. Sadly, such low-probability, high-impact tragedies happen during the friendliest mass gatherings and with little warning.

The crowd-dynamics research community strives to understand a broad range of human collective behavior—from stampedes like the one in San Carlo Square to pedestrian motion on sidewalks. That interdisciplinary effort has led to several advances, such as continuum hydrodynamic models that treat crowds as fluids and computer-vision techniques that detect anomalous behavior of thieves in public places. Those approaches work well when the crowd density is fairly low and people are generally able to move toward an intended destination.

But when the density reaches the level found at rock concerts, parades, and pilgrimages, people start to bump and press against each other. The physical properties of the crowd are no longer fluid-like but instead are closer to soft solids and granular materials. At such densities, pedestrians can be modeled as self-propelled particles subject to forces that represent social and physical interactions. Even though those social force models are simplifications of real crowds and require careful calibration to be predictive, they can qualitatively reproduce emergent crowd dynamics (see the Quick Study by Andrea Welsh, Edwin Greco, and Flavio Fenton, PHYSICS TODAY, February 2017, page 78). More generally, analogies between human crowds and physical systems have repeatedly demonstrated their utility for understanding crowd collective motion.

Conceptual analogies

A classic model for crystals is the ball-and-spring network, in which balls are positioned on a regular lattice and springs connecting nearest neighbors represent interactions given by physical potentials. That model leads to an exact expression for the dispersion relation, which relates the frequency and wavelength of vibrations propagating across the crystalline lattice. The vibrations are the lattice's elementary excitations and are essential for understanding bulk material properties, such as heat capacity and thermal conductivity. Vibrational modes thus provide a bridge between the large-scale collective properties of the crystal and the small-scale physical interactions of neighboring balls. When studying dense groups of people, modes are similarly useful because they relate large-scale collective crowd motion to the underlying network of physical contacts between people.

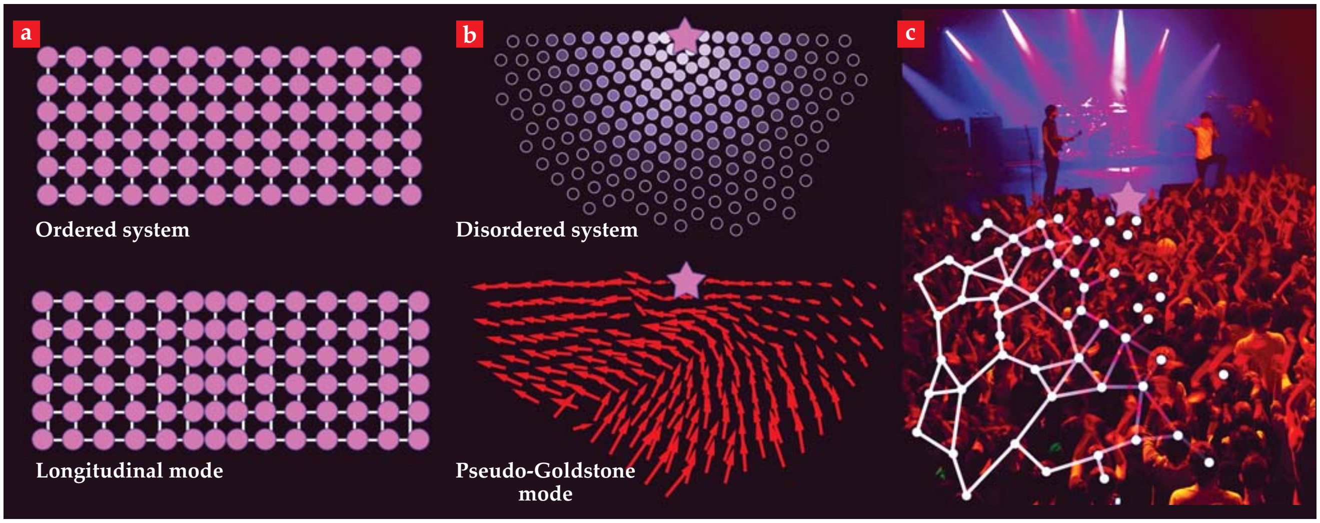
Examples abound of noncrystalline solids in industrial and technological applications: sand, coffee beans, and highly packed wheat grains, among others. Unlike crystals, granular materials exhibit a disordered, self-organized structure generated by complex interactions between grains (see the article by Anita Mehta, Gary Barker, and Jean-Marc Luck, PHYSICS TODAY, May 2009, page 40). To understand the properties of those and similarly dense and disordered systems, physicists have adopted an approach closely related to that used for studying crystalline solids.

When modeling grains and their interactions as a ball-and-spring network, physicists replace the regular lattice configuration of crystals with a quenched disorder—that is, a disorder frozen in time. Although that model was originally developed for granular materials, the disordered structure of the packings in two dimensions resembles that found in high-density crowds. And regardless of why a system might be disordered, one can ask how such disorder affects vibrational properties.

When scientists compute the modes for disordered packings, they find that the familiar system-spanning vibrations are almost entirely replaced by spatially localized vibrational patterns, typically correlated over a few neighboring grains. Three points are relevant. First, the specific spatial pattern of the localized vibrations is deeply connected with the underlying disorder. Second, disordered systems have an excess of low-energy, easily excited modes compared with those found in crystals. Those modes are quasi-localized, meaning they extend over a characteristic length scale—larger than a few grains but smaller than the system. Thus, when excited, they drive motion over the corresponding length scale. Third, grains are not constrained by a lattice structure, so they can rearrange their positions.

Vibrational analysis is a powerful tool for studying crowd dynamics because unlike more traditional approaches using force models, no crowd-system model needs to be built or calibrated. At its heart, the technique produces a correlation matrix that converts apparently random displacements of grains about their equilibrium position into specific predictions of coordinated motion.

Four years ago we had the idea to apply mode analysis to a simple, social-force model of crowds attracted to a point of interest, such as the stage of a rock concert, as shown in the



COLLECTIVE MOTION IN DENSE CROWDS. An ordered lattice **(a)** exhibits long-range collective motion in the form of vibrational modes, such as the longitudinal mode. **(b)** Individuals in a dense crowd gathering at a point of interest (star) pack into a disordered blob—the greater the pressure among people (dots), the brighter they are—with their own emergent, long-range, collective motion. The pseudo-Goldstone mode, represented by a vector field (arrows), is an example of such collective motion. **(c)** Empirical data collection at rock concerts can be used to extract the crowd's vibrational modes that arise from the underlying contact network (nodes and links). (Photo courtesy of Ulrike Biets.)

figure. In addition to verifying the spatially localized modes common to other granular systems, we found that the lowest-energy mode extends across the entire system and gives rise to a bulk-scale collective motion. The excitation is so special that it has its own name—the pseudo-Goldstone mode—and is known to originate from the model's broken translational symmetry. In this case, symmetry is broken by a point of interest that attracts the crowd.

Whether that collective motion is activated in a given crowd depends on how the crowd is perturbed and on how much energy comes from the perturbations. Testing that dependence and measuring the minimum perturbation energy needed to activate a pseudo-Goldstone mode requires fieldwork to gather video data on real crowds in high-density conditions.

Emergent collective motion can be activated in various settings—concerts, Black Friday sales, protests, religious pilgrimages, and sporting events, among others—simply because high-density crowds are disordered systems. Furthermore, the fact that pseudo-Goldstone modes have low energetic costs could explain why the density waves and their associated deadly pressures can emerge without notice and propagate across a crowd.

Ethics and experiments

Physical models of crowds explore a simplified model of reality, but how do they stack up to real groups of people? Can the models explain human psychology? How much energy is required to activate a pseudo-Goldstone mode? It's difficult to answer those questions without evidence, so we naturally turn to empirical data. Right away we run into a problem: It's not ethical to trigger a crowd disaster for the sake of science. And yet little observational data on crowd disasters is available for the vibrational-mode analysis described here.

What makes for good observational data? Ideally, one would have coordinates $[x_i(t), y_i(t)]$ for all $i = 1, \ldots, N$ people in the crowd over a period of time lasting minutes to hours. In the absence of volunteers who would wear tracking devices, we could extract the information from quantitative image analysis applied to security-camera footage. That approach requires an elevated, stationary, and continuous view of as much of the crowd as possible. Even so, predictions for collective motion cannot be validated unless it actually occurs. Given the significant potential for injury during such motions, we find ourselves in the dismaying position where we both do and don't want to observe their emergence.

The path ahead

What's next for collective motion studies of high-density crowds? Because research ethics rule out broad categories of experiments, we plan to take an observational approach to press several questions. Can a pseudo-Goldstone mode be measured in a real crowd? If so, does it predict the crowd's actual collective motion? Can the analyses be used to prevent crowd disasters?

Fortunately, we happen to enjoy going to concerts, and if you've ever been to a hard-rock show, you're already well aware of the high crowd densities near the band stage and of the way crowds tend to move as a collective whole. The path ahead? We're going to concerts. And we're taking our cameras.

Additional resources

▶ S. Henkes, C. Brito, O. Dauchot, "Extracting vibrational modes from fluctuations: A pedagogical discussion," *Soft Matter* **8**, 6092 (2012).

▶ A. Bottinelli, D. T. J. Sumpter, J. L. Silverberg, "Emergent structural mechanisms for high-density collective motion inspired by human crowds," *Phys. Rev. Lett.* **117**, 228301 (2016).

▶ J. L. Silverberg et al., "Collective motion of humans in mosh and circle pits at heavy metal concerts," *Phys. Rev. Lett.* **110**, 228701 (2013).

▶ D. C. Duives, W. Daamen, S. P. Hoogendoorn, "State-of-the-art crowd motion simulation models," *Transp. Res. Part C: Emerg. Technol.* **37**, 193 (2013).

▶ D. Helbing, A. Johansson, H. Z. Al-Abideen, "Dynamics of crowd disasters: An empirical study," *Phys. Rev. E* **75**, 046109 (2007). PT