

Dense crowds follow their own rules

When thousands of people are packed into a confined space, collective dynamics takes over. The phenomenon can be described with a physical model.

“If you want to know why there are riots at some football games, and not at Caltech football games,” said then-Caltech professor John Hopfield to an audience at the 1983 Corporate Associates meeting of the American Institute of Physics, “it has to do simply with the scale: 10 people don’t riot!”¹

It was a flippant comment in support of a broader point. In a large enough gathering of anything—whether atoms, cells, insects, or people—collective phenomena emerge that are completely different from anything one might see in smaller groups of the same constituents. Moreover, the collective behaviors can often be meaningfully understood without appealing to the interactions of the individuals at all.

Hopfield was interested in collective behaviors of neurons, and for his work he was awarded a share of last year’s Nobel Prize in Physics (see *PHYSICS TODAY*, December 2024, page 12). But similar principles have come to underlie the field of active-matter physics, in which the tools of areas such as statistical mechanics and fluid dynamics are brought to bear on colonies of bacteria, schools of fish, and more. (See, for example, *PHYSICS TODAY*, July 2023, page 14.)

Now Denis Bartolo, of the École Normale Supérieure (ENS) de Lyon in France, and colleagues have used active-matter techniques² to study large, dense crowds of humans—in particular, the opening ceremony of the San Fermín festival in Pamplona, Spain, which draws some 5000 people to the plaza shown in figure 1 each year on 6 July. From video footage they took of the ceremony, they modeled the crowd not as a collection of individuals but as a continuous medium. Their approach is similar to how one might describe the turbulent flow of a fluid from its bulk properties, such as viscos-



FIGURE 1. THE SAN FERMÍN FESTIVAL in Pamplona, Spain, is perhaps best known for the running of the bulls through the streets each 7–14 July. The festivities kick off on 6 July with the opening ceremony, which attracts thousands of revelers to the plaza in front of the Pamplona city hall. Shown here is the beginning of the ceremony, in which security personnel (dressed in blue) and musicians (wearing white) emerge from the city hall and move through the crowd of revelers (whose white clothes by this point are stained pink with sangria). In the hour leading up to the ceremony, the crowd gradually assembles, grows denser, and displays collective dynamics. (Photo courtesy of the Bartolo Lab, ENS de Lyon.)

ity and density, rather than its intermolecular forces.

The researchers gained new insight into the unusual collective behaviors that emerge in dense crowds only at large scale. Contrary to Hopfield’s remark, large crowds don’t inevitably result in riots. But they do consistently give rise to periodic orbital motion characterized by spontaneous symmetry breaking.

Crowds in the wild

It’s not that physicists have never tried to study crowd dynamics before. (See, for example, the Quick Study by Arianna Bottinelli and Jesse Silverberg, *PHYSICS TODAY*, September 2019, page 70.) But their efforts have been stymied by a lack of data. As Bartolo puts it, “It’s very difficult to test a model if you don’t have anything to model.”

The same goes for studies of groups of other large animals. Microscopic active-matter systems, such as cells and tissue cultures, lend themselves easily to lab experiments, and they’ve been studied thoroughly. “But you can’t invite thousands of zebras or wildebeest into your physics department,” says Bartolo. “You can’t push on them with a macroscopic rheometer and measure the response. You have to rely on real-world observations.”

A few thousand people are easier to come by than a few thousand zebras. But studies of human crowds are subject to a further complicating factor: safety. The extremely dense regime that Bartolo and colleagues were most interested in is also the most dangerous. For example, an out-of-control dense crowd at the 2010 Love Parade, a music festival in Duisburg, Germany, caused the deaths

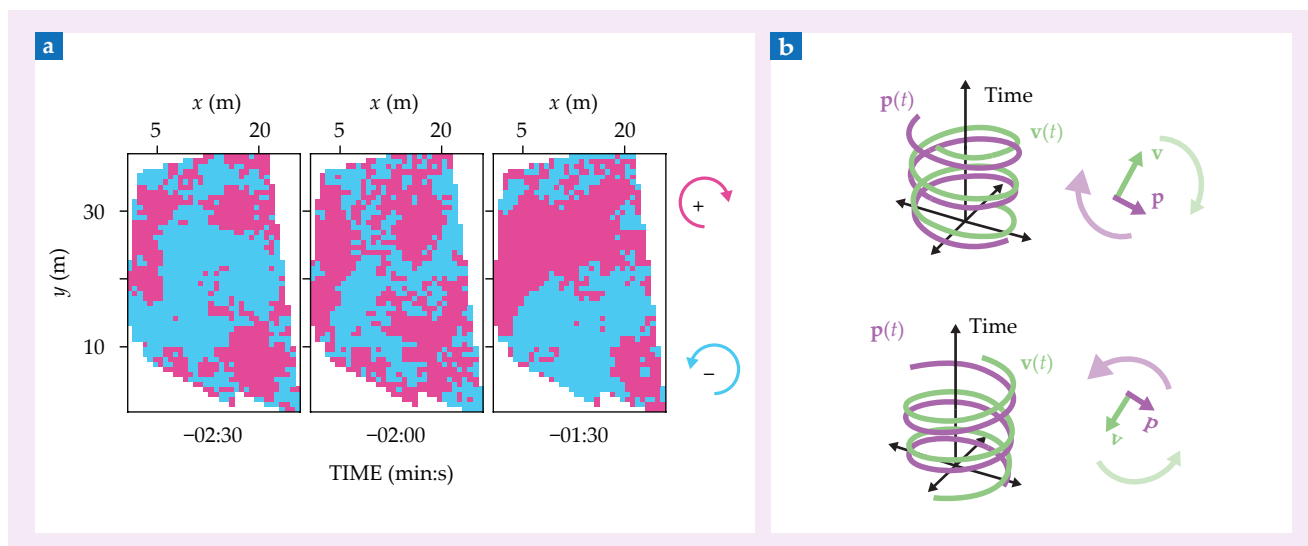


FIGURE 2. MIRROR SYMMETRY is locally broken by the eddy-like undulations in a dense crowd. **(a)** The crowd as a whole, however, has no collective preference for clockwise or counterclockwise oscillations, as seen in these three plots of the handedness of the 2023 San Fermín crowd in the minutes before the opening ceremony. **(b)** An active-matter model shows how the symmetry can be broken spontaneously by initial conditions. In the model, the state of the crowd at time t is characterized by the velocity field $\mathbf{v}$ and the propulsive force field $\mathbf{p}$. The two vectors rotate in tandem, with the direction of the rotation determined by their initial relative orientations. (Images adapted from ref. 2.)

of 21 people and injured hundreds more. As a result, the Love Parade, which had been a regular event since 1989, was permanently canceled.

The San Fermín festival presents a happy counterexample. Its opening ceremony has been held for over a century, and although the assembled crowd becomes almost unimaginably dense—with up to nine people per square meter in some spots—no serious injuries have ever been reported. It was an ideal site for a large-scale, reproducible active-matter study.

Breaking symmetry

Bartolo's coauthor Iker Zuriguel, of the University of Navarra in Pamplona, had a friend of a friend who owned an apartment with a view of the plaza where the ceremony is held. And Zuriguel made arrangements with the Pamplona city council to allow the researchers to film the crowd.

The first observations were conducted in 2019—an unlucky time to start, because the COVID-19 pandemic canceled the festival in 2020 and 2021. But the researchers returned in 2022, and during the next three festivals, they started to notice some common features in the crowd.

In the hour leading up to the opening ceremony at noon, the crowd assembles gradually, so the researchers can observe

the crowd dynamics as a function of density. Above a critical density of about four people per square meter, the crowd starts to undulate in quasiperiodic circular orbits.

Crowd undulations had been observed before. Participants in the 2010 Love Parade crowd reported a feeling of being jostled back and forth in a wave-like motion,³ and observers of that and other dense crowds have described the scenes as “turbulent” or “chaotic.” But with the help of machine-learning software that automatically tracked the trajectories of all the individuals in the San Fermín festival crowd, Bartolo and colleagues concluded that “turbulent” was not the right word to describe it at all.

In an ordinary fluid, turbulence is characterized by unpredictable motion, eddies that span a vast range of size and time scales, and mixing of the system over time. Bartolo and colleagues didn't observe any of those things. Members of the San Fermín crowds did follow eddy-like orbits, but they predictably circled back to close to their initial positions in an extraordinarily consistent time of 18 seconds—a much longer time scale than the periodicity of any isolated human movement.

Another clue about what's behind the undulations comes from their geometry. A circular orbit in two dimensions breaks mirror symmetry: A clockwise orbit is

different from a counterclockwise one. Various causes could give rise to the symmetry breaking. For example, most people are right-handed, and most members of the San Fermín crowd come from countries where people drive on the right. For either of those reasons, or similar ones, revelers at the San Fermín festival may have an instinctive preference to dodge one way instead of the other in a crowded environment.⁴

But if they do, that's irrelevant, Bartolo and colleagues found, because the crowd as a whole doesn't collectively prefer one orbital direction over the other. As figure 2a shows for three snapshots of the 2023 crowd, clockwise and counterclockwise orbits are evenly mixed, and their spatial distribution is not constant. An analysis of all the data from each year showed the same thing: a near-even split between clockwise and counterclockwise, with many individuals switching between both.

A sea of people

If the orbital undulations don't stem from individual actions, where do they come from? To shed some light on the question, Bartolo and colleagues modeled the crowd as a continuous medium rather than a collection of individuals. Like any physical system, it had to obey Newton's second law: The local velocity $\mathbf{v}$

of the medium changes in proportion to the net force applied to it. Because the medium is made up of people, who are capable of moving under their own power but not perfectly free to choose how they do so, the net force includes a propulsive term $\mathbf{p}$.

Both $\mathbf{v}$ and $\mathbf{p}$ are vector fields that depend on position and time. Assuming that those two quantities completely characterize the state of the crowd, the researchers wrote down a general model of all the ways that each quantity could deterministically evolve in time. And they found a term that could be key to describing the undulations: $\mathbf{p}$ changes in time in proportion to $-(\mathbf{p} \times \mathbf{v}) \times \mathbf{p}$.

The first part of the vector product, $\mathbf{p} \times \mathbf{v}$, always points perpendicular to the plane of the crowd, but whether it points up or down depends on whether $\mathbf{p}$ is angled to the right or the left of $\mathbf{v}$. The net effect of $-(\mathbf{p} \times \mathbf{v}) \times \mathbf{p}$ is always to rotate $\mathbf{p}$ away from $\mathbf{v}$. But because $\mathbf{p}$ is a force that acts on $\mathbf{v}$, $\mathbf{v}$ also rotates in the same direction. The result, shown in figure 2b, is that $\mathbf{p}$ and $\mathbf{v}$ circle around and around in tandem; whether they circle clockwise or counterclockwise depends on how they were oriented to begin with. That is, the mirror symmetry is spontaneously broken by the initial conditions.

The model agrees well with the undulations observed in the San Fermín crowds, and it's even consistent with the crowd dynamics at the 2010 Love Parade, as inferred from sparser and grainier video footage of that event. The physical origins of the $-(\mathbf{p} \times \mathbf{v}) \times \mathbf{p}$ term are

still murky, but the larger insight is that crowd dynamics can be described by a continuum model at all.

"A group of five people is not suitable to be described with these tools," says Bartolo, just like it wouldn't make sense to use the equations of fluid dynamics to model a cluster of five molecules. "What is the magic number of people where the individual interactions get averaged out? We weren't sure that the San Fermín crowds would be over that threshold. But they were, and we're very happy about that."

Safety in numbers?

The continuum model offers a framework for thinking about what makes dense crowds dangerous in some circumstances but not others. The undulations are an emergent property of the crowd itself, and they're not under the individuals' control. They involve the correlated, collective motion of tens to hundreds of people, with a combined mass of up to tens of thousands of kilograms. If such a group slams into a wall—with no one having the power to stop it—it can exert a crushing force with deadly consequences.

The Pamplona plaza is surrounded by walls. But it also has plenty of side streets that can act as pressure relief valves if too much of the crowd gets compressed near the edge of the square. The Love Parade disaster, in contrast, occurred in the narrow entranceway to the festival grounds, where escape routes were limited. The difference could be key to understanding why the Love Parade

ended in tragedy, whereas the San Fermín opening ceremony never has.

Bartolo also points out that crowd undulations start small and grow larger as the crowd density increases. So looking for the undulations while they're still small could be a way for event organizers to tell when a crowd is on the verge of becoming dangerously out of control. "Engineers will have to work hard to develop concrete applications that will prevent real catastrophes," says Bartolo. "But we do think this is potentially useful."

So far, the researchers have limited their study to the average dynamics of the crowd as a whole. They'd like to extend their model to describe how crowds respond to localized stimuli, and they suspect that such an investigation could help clarify the connection between individual behaviors and continuum crowd dynamics. The San Fermín opening ceremony could again provide the setting for a natural experiment, as musicians and security personnel emerge from the city hall and move through the crowd. And every 6 July presents a new chance to gather more data.

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References

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Plasma channel guides electrons to 10 GeV

Femtosecond-scale laser pulses make a plasma waveguide that helps wakefield-surfing electron bunches keep their energy focused.

High-energy, ultrafast-moving particles have a wide array of both applied and fundamental scientific uses, such as imaging biological tissue in detail and probing questions about the building blocks of matter. But accelerating parti-

cles to high energies is not a cheap or easy task. The advanced accelerators being used for that purpose rely on multikilometer-scale facilities. That's because RF cavities—metal chambers that generate the electric fields used to accelerate particles—have fundamental limits that max out their electric field gradients at tens of megaelectron volts per meter. At those gradients, it takes kilometers to get particles up to the tens of gigaelectron-volt energies achieved at facilities such as SLAC and the German Electron Synchrotron (DESY). But

there's another approach that can produce electric field gradients that are thousands of times as strong as those produced in RF cavities.

When a laser pulse is sent through an ionized plasma—a sea of electrons and ions—it pushes aside the lighter electrons. The charge rearrangement induces a strong electric field gradient that moves like a wave through the plasma and trails behind the front of the laser pulse, as shown in figure 1. Much like a surfer can ride the wake behind a speedboat, electrons can get trapped in the plasma wave