What happens if...?

Every physicist probably has a favourite experiment, some example from history, recent or remote, of a clever set-up that cut through a mess of obscuring detail to reveal some phenomenon with jaw-dropping clarity. It might be Cavendish's experiment of 1798, which measured the gravitational force between masses by suspending them from a torsional pendulum. Or James Joule's demonstration of the conversion of mechanical energy to heat. Or perhaps some recent experiment in quantum information or computational astrophysics.

Typically, a really beautiful experiment weds disarming simplicity of design or conception with a stunningly non-intuitive outcome. On that score, one of my all-time favourites was undertaken just over 15 years ago by some physicists at the University of Texas. In principle, it might have been done in 1900, or even earlier — say 1750. Conceptually, it could hardly be simpler, but no one ever thought it worth doing.

The experiment is best presented as an open question. Suppose you take a simple container, such as a petri dish, and put in a thin layer of ball bearings, about 1 mm deep. You put a cover on the container and then begin shaking it up and down, with minimal sideways movement. You can control the amplitude, A, and frequency, f, of the shaking. The question is: as you shake the dish ever more energetically, increasing both amplitude and frequency, will anything interesting happen?

I readily admit that when I first heard about this experiment, all my instincts said "no". Obviously, when the shaking gets hard enough, the beads will start flying into the air. They will collide with one another, creating chaotic motion and something roughly akin to a gas of ball bearings. Shake the dish still harder and faster and it is difficult to imagine anything much changing. I couldn't, at least.

I also couldn't have been more wrong. Much of the genius of a great experimental scientist lies in letting reality speak for itself, without censoring it with preconceived expectations. This is what Paul Umbanhowar, Francisco Melo and Harry Swinney managed to do (*Nature* **382,** 793–796; 1996). They found that with sufficiently vigorous shaking, the chaos suddenly transforms into order. The uniform layer of beads gives way to striking spatial patterns of wavelike variation across the dish, the patterns typically fluctuating (from density maxima to minima) at half or one quarter of the driving frequency. (The patterns they witnessed can be seen in the original paper).

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The 'vigour' of shaking can be measured as the maximum acceleration of the dish, this being equal to $4\pi^2 f^2 A$. Ordered patterns, in the form of stripes or squares depending on the frequency, first appear when this is about 3.3g (g being the acceleration of gravity); at higher accelerations, a zoo of further patterns emerges. The stripes or squares first turn into hexagons, then a variety of other more complicated configurations, before these ordered structures ultimately undergo a kind of 'melting' into disordered, ever-changing structures at very high forcing. The experiments also established that the patterns obtained don't depend on the shape and size of the container as long as the diameter is much larger than the wavelength of the patterns. They seem to reflect the behaviour of the bead system, not the container it is in.

How to explain why these patterns grow? Things are a little simpler than one might think, because whenever the bead layer rises off the cell floor and then slams down again, it doesn't bounce. Collisions between beads absorb the energy. Hence, the layer moves more or less as a coherent whole. Umbanhowar and colleages explained the various transitions by considering how the layer time-of-flight may sometimes change discontinuously with increased forcing, and how the layer on impact may dilate so as to lower its potential energy by falling into spatially structured arrangements. Details aside, the basic story is that any small deviation sets up conditions that tend to channel beads in the next cycle, creating further deviations from uniformity. This feedback drives a pattern that grows until it settles into one of the observed structures.

There's more. In certain intervals of frequency and amplitude, the original experiment also revealed stranger patterns that the authors dubbed 'oscillons'. These aren't spatially periodic waves extending through the dish, but localized structures, oscillating at half the driving frequency between density peaks and troughs, and persisting for long periods of time (as an example, see this image: http://go.nature.com/T9fNxG). These oscillons act like independent particle-like objects in their own right, able to collide, repel or annihilate given the right circumstances.

Often when I give presentations to non-scientists, I use this experiment as an example of how, when lots of things interact, our intuition is almost useless in predicting what might happen. It's pretty clear that nothing about the beads themselves determines the patterns; the organization is a global phenomenon. This extended system, when its parts interact strongly enough, becomes a kind of physical medium. Interactions really do matter more than parts.

But these experiments, beauty aside, have also kicked off a whole field of research. Noting that the properties of the beads seem to have little to do with the patterns, Umbanhowar and colleagues speculated that similar patterns, both extended and localized, might be found in completely different systems. This was subsequently confirmed in shallow layers of various fluids driven by vibrations. And there are tantalizing signs of a deep link between the extended patterns and the localized oscillons.

At high forcing, when the spatially ordered patterns ultimately melt into a disordered 'liquid', it looks like the wave-like structures simply lose coherence. Yet researchers in the past few years — working with both granular and fluid systems — have demonstrated that this transition to disorder can be understood as an ordinary melting transition in which the 'atoms' are actually oscillons put together to make up the pattern. The extended patterns, and the oscillons, seem to be different manifestations of one underlying physical order.

All this rich mystery from an experiment that no ordinary and sensible person would ever bother to do, it being so obvious that nothing interesting would come of it. But I guess that's physics. Repeated contact with nature provides the best education for the imagination. ❐

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