Drum roll

In 1939, a Japanese engineer named Yositisi Oyama reported a curious phenomenon he'd observed in his laboratory. Oyama had placed a mixture of limestone particles of two different sizes into a transparent cylinder or drum, making it about half full, and then started the cylinder rotating about its long axis at a constant speed. After a time, the mixture of pebbles didn't stay mixed together, large mingling with small, but instead segregated by size, forming a striking series of bands characterized by smaller or larger particles. Order all on its own.

Segregation phenomena like this had been shown before, of course, if not studied quite so scientifically. In 1904, in fact, the American inventor Thomas Edison applied for a patent on a device designed to destroy similar patterns in a rotating cylindrical device used for cement mixing (J. Ottino, *Chemical Engineering Science* **61,** 4165–4171; 2006).

Today, spontaneous pattern formation of this kind — in gravels and granular matter of all kinds such as seeds and powders, in fluids or plasmas, even in bacterial colonies or human crowds — is no longer surprising. The field is highly developed both experimentally and theoretically on the basis of applied dynamical systems theory. Yet the simple rotating drum set-up of Oyama still holds plenty of secrets — it's a simple experimental paradigm exhibiting an almost endless variety of novel behaviours.

If the phrase 'rotating drum flow' suggests a relatively simple system characterized by only a few parameters, this is actually deeply misleading. One can vary the size of the drum, or its aspect ratio or speed of rotation. The drum may be fully or only partially filled with beads or grains, which can be slippery or sticky. The drum may be filled with a liquid, or a liquid with bubbles or grains in it. Two or more different kinds of grains can be used. Even in the simple case of a mixture of grains of two different kinds, as Gabriel Seiden and Peter Thomas point out in a forthcoming review article (*Reviews of Modern Physics*; in the press), the system is characterized by seven dimensionless parameters, creating a large universe of possible dynamics.

Some recent experiments closely related to Oyama's illustrate the beauty of rotating drum physics. For one thing, you don't really need a drum. Frank Rietz and Ralf Stannarius have used a thin box or Hele-Shaw cell formed from two transparent sheets sandwiching a 5 mm gap, which is

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essentially a drum that has been strongly squeezed in one dimension. They put glass beads into the gap and used the set-up to examine how segregation dynamics might depend on the filling ratio — that is, how much of the total volume is occupied by beads (*Phys. Rev. Lett.* **100,** 078002; 2008).

Surprisingly, the fill ratio matters a lot. They found that the grains acted pretty much like they did in Oyama's experiment, except when the box is filled right up to the top, and then things change abruptly and dramatically. The fraction of filled volume, C, cannot ever get as high as 1, of course, as beads won't pack a volume completely. The maximum in these experiments was roughly $C = 0.7$. For C below a critical value of about 0.6, Rietz and Stannarius found that the beads acted as Oyama had observed — they quickly segregated (within a few hundred turns of the box) to form a banded pattern along the axis with alternating stripes of small and large particles. These stripes gradually grew wider and some eventually coalesced to create two or three stable segregated regions.

Things changed when they added more beads to the box, pushing the filling fraction C above the critical value. At this point, putting a few more grains into the container leads to jamming of the granular motion. Whereas gravity had driven the grains to flow first one way than the other (so-called chute flow), the beads now got locked into a dense, packed state unable to flow in the same way. Above the critical filling fraction, most of the motion within the container now came as groups of beads moved together in jammed clusters — much as happens in glassy substances when they begin to freeze.

But the result in this case, paradoxically, isn't fixation of the striped segregation, but its dissolution into something at least visually more dynamic. Rietz and Stannarius found that the beads formed a series of convection rolls along the cylinder, which persisted in a stable form (their video, at http://go.nature.com/g16iG8, communicates the qualitative results best). It's clear that the sharpness of the effect is due to the onset of jamming in the granular flow, which happens quickly near the critical fill level. The nature of the instability driving the convective motion, however, remains mysterious.

Also mysterious is whether this transition to convection has a close relative if the squeezed Hele-Shaw cell expands back to become a full three-dimensional cylinder. As Seiden and Thomas note, experiments performed using a rotating drum at very high filling fractions did find signs of convection at least somewhat similar to that observed by Rietz and Stannarius. In these experiments (S. Inagaki & K. Yoshikawa, *Phys. Rev. Lett.* **105,** 118001; 2010), the axial bands, once formed in the middle of the drum, move toward the ends as travelling waves. But that movement visible on the outside surface of the drum wasn't shared inside the drum, where a complex convective flow brought material back to the drum centre.

The similarities with the two-dimensional flow are striking if qualitative. In particular, in both experiments the inner core of the drum or cell remained mostly well mixed, while the intermediate region consisted purely of the smaller of the two grains or beads used. As with much of physics, one finds here a competition between two trends — a progressive linking together of apparently disparate phenomena, and also a proliferation of novelties.

Replace grains with a mixture of fluid and grains, and you find again phenomena both similar and different. Experiments find the ready emergence of axial bands of high particle concentration. Yet theoretical models still struggle to explain precisely what drives this segregation, and theory cannot presently explain why in some cases the bands develop a fine structure of several rings, something not yet seen in granular flows.

And really, we're only beginning to explore rotating drum flow — how about drums (squashed or otherwise) containing more than one liquid, or flows of non-Newtonian liquids, including polymer solutions? This is a clear case where fascinating physics gets tossed forth by engineering problems, as industry uses rotating drums in everything from making paper or transporting flour, sand, seeds and cement. Edison knew that a century ago. ❐

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