Grain of truth

The argument has been made countless times that some thing, X, whatever it might be, cannot possibly cause some other thing, Y, because X is just far too small, weak, slow, short-lived and so on. Sceptics of both evolution and plate tectonics argued that their predicted mechanisms required outrageous amounts of time to shape species and mountains, and other such effects — thousands, millions of years, even more. Clearly absurd. Don't worry, people argued early last century, mankind is far too insignificant to ever pollute the vast rivers or the atmosphere. Change the climate? Don't be silly.

What impossibility proofs of this kind mostly illustrate is lack of imagination. Or perhaps we should say, a mismatch between the human mind and the world around it, where effects often work along pathways too convoluted for us to see. It is the simplest examples that bring this mismatch into strongest relief, and they are, as a rule, discovered by accident.

In the early 1990s, when Andrea Liu and Sidney Nagel were studying the propagation of acoustic waves through a granular system of glass beads, they found that the signal attenuation over distances of a few centimetres was surprisingly hard to measure in a consistent way. Values changed erratically from one experiment to the next. Ultimately, they identified what was happening. As they wrote: "A temperature change of only 0.04 K inside the pile, produced by the change of the ambient temperature could cause a factor of three reversible change in the measured vibration transmission" (*Phys. Rev. Lett.* **68,** 2301; 1992).

But wait — temperature? Is that possible? Think of it. The amount of energy involved in a grain tumbling through a distance equivalent to its own diameter d — an estimate of the scale of energy involved in pile rearrangements — is roughly $\rho g d^4$, with ρ the density. The amount of energy delivered to a grain by thermal noise at temperature T is roughly kT. At room temperature, the ratio works out to be $\rho g d^4/kT \approx 10^{11}$.

Hence, it seems that thermal noise is roughly 100 billion times too weak to have any effect on the arrangement of the grains. Temperature changes just shouldn't matter. Tap a box of sand gently with your hand and you can easily dislodge a few grains, but you are putting in 100 billion times more energy than gets put in by thermal fluctuations.

This is a metaphor for the nature of human thinking, and the habit of seeing what is or isn't possible.

Of course, this impeccable logic turns out to be totally wrong, for temperature changes work their effects through pathways having little to do with energy or thermal noise, and everything to do with altering patterns of stress and connection within the pile. These patterns have an extraordinary sensitivity to the tiniest changes in external conditions.

This was first noted in the late 1990s in experiments with granular matter in a silo. Fill a small silo with glass beads, and measure the weight they project onto the floor. Now take them out, and do it again. Experiments doing this repeatedly found variations in the weight as large as 20%, even though the exact same beads were being put back in each time. The secret is that grains, because they make frictional contacts with the walls, can hang some of the pile's weight on those walls; it doesn't all go down to the floor, as in a liquid. How much hangs on the walls depends on the precise pattern by which particles link together — whether 'arches' carrying stress terminate on the floor or on a wall. This can easily change from one filling to the next.

Computer simulations also show that tiny changes in particle stickiness can have similarly huge effects. For example, Philippe Claudin and Jean-Philippe Bouchaud found that a variation of the grains' friction coefficient of only one part in ten million could trigger a large-scale reorganization of stress lines within the pile — what they called 'static avalanches' (*Phys. Rev. Lett.* **78,** 231; 1997). The pile doesn't move, looks outwardly the same, yet undergoes a complete reorganization of internal stress.

In effect, this was an implicit demonstration that temperature might well influence granular dynamics, despite the seemingly insurmountable factor-of-10^{11} energy mismatch. Since then, a series of further experiments has indeed confirmed the effect.

As Thibaut Divoux points out in a recent review (*Pap. Phys.* **2,** 020006; 2010), for example, temperature variations of less than a degree should be plenty large enough to create friction changes on the scale studied in Claudin and Bouchaud's simulations. That's because temperature changes naturally cause the dilation of grains. Such dilation ought to influence frictional contacts when it takes place on a scale comparable to the surface roughness of the particles — it should then be sufficient to alter how the rough surfaces lock together. For standard glass beads, an estimate gives a required temperature change of only 0.1 of a degree.

Hence, it is not actually surprising that experiments now routinely demonstrate such effects. It is well known that a granular pile can be compacted by repeated gentle tapping, and the same turns out to be true for thermal cycling. Experiments over the past few years have tested the progressive packing of glass or polyethylene spheres held in rigid cylinders exposed to cyclic heating and cooling. They show the pile growing progressively more dense as temperature changes allow stress patterns to reorganize, occasionally releasing the least strongly bound particles, which can fall (the density shows a slowing glass-like logarithmic growth at long times).

Again, it's not that the temperature changes simply cause the grains to expand and contract. The compacting remains unchanged in experiments using beads with a higher or lower coefficient of thermal expansion. The behaviour, rather, reflects how a small expansion of grains throughout the entire pile can be focused and amplified to create large consequences at local points of contact between specific grains. The pile is controlled by a branching process of exquisite complexity, impossible to predict in detail, yet reliable in operation.

This is actually a nice metaphor (and perhaps more) for the nature of human thinking itself, and the habit of clearly seeing what is or is not possible. We're trapped, it seems, by intuition into believing that we can extrapolate from known to unknown, and at least see the plausible and likely rearrangements of our knowledge. But we always underestimate the amplifying effects of every small error, which build so quickly that everything we once thought right turns out to be totally wrong, even if it did once seem so obvious. ❒

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