MATERIALS SCIENCE

On Mixing and Demixing

Insights into the physics of mixing are leading to methods for avoiding segregation of different particles.

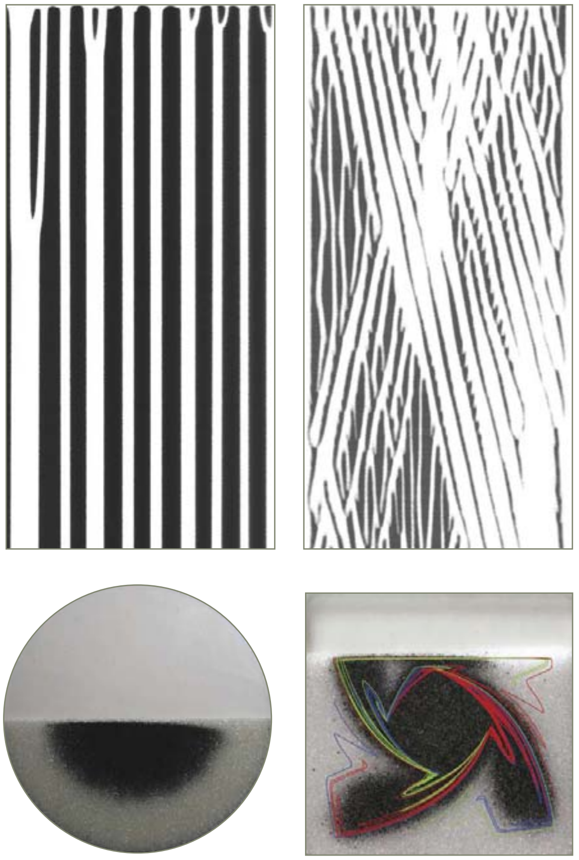
Julio M. Ottino and Richard M. Lueptow

Trying to mix two dissimilar granular materials—such as light and heavy or small and large particles—may lead to counterintuitive results: Putting more and more energy into mixing may actually result in more and more demixing (*1–5*). The robust and varied patterns resulting from demixing (see the first figure) have long puzzled practitioners and researchers alike. How can one mix something that does not want to mix? Recently, Shi *et al.* have devised a conceptual approach that may allow for the mixing of dissimilar granular materials based on the fundamental physics of granular flow (*6*).

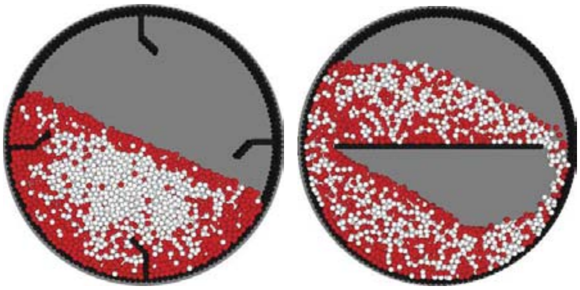
The first studies of granular mixing were of an engineering nature: "How can we mix this?" This targeted approach was successful in many practical applications. However, it provided few insights into the causes of demixing and did not yield general solutions to new segregation problems encountered in the processing of pharmaceuticals, dry chemicals, ceramics, minerals, polymers, and powdered or granular foodstuffs.

The origin of demixing seems counterintuitive at first glance: One might expect particles tumbling down a slope to mix as they flow. Nevertheless, simple cases of demixing can be explained in terms of the percolation of small particles through interstices between large particles or due to "buoyancy" differences between light and heavy particles. The small or heavy particles drift to lower portions of the flowing layer and thus fall out of the flowing layer earlier than large or light particles (see the first figure, bottom left).

Other segregation patterns can occur for various combinations of particle sizes and densities (*7*), whether the particles are surrounded by air or wholly immersed in a liquid (*8*). Predicting these patterns is challenging, because granular matter provides an example of "more is different" (*9*): The behavior of one or a few elements does not capture the behavior of many elements, so that segregation patterns cannot be deduced from the behavior of individual particles.



Demixing patterns. (**Top**) Upon rotation, a long cylindrical tumbler partially filled with a homogeneous mixture of two sizes of particles will segregate into bands. Space (horizontal) and time (vertical from top to bottom) plots show coarsening (left) and waves (right), depending on the rotational speed and interstitial fluid (*19*). (**Bottom**) In a circular tumbler, small particles segregate into a semicircular pattern (dark) surrounded by large particles (light) within one or two rotations (left) (*7*); in a square tumbler, similar particles segregate into a lobed pattern outlined by unstable manifolds (right) (*20*).



Mixing and demixing. In simulations of bidisperse mixtures of particles with different densities, short baffles added to the wall of the tumbler do little to enhance mixing (**left**), whereas a central baffle truncates the flowing layer, leading to good mixing (**right**) (*6*).

In recent years, there has been a surge of systematic studies of granular flow under a wide range of experimental conditions, including, for example, how flow is affected by the interstitial fluid, the adhesive properties of the particles, and changes in gravity (*10*). Other studies have investigated the rheology of granular flows in an attempt to develop appropriate constitutive relations (*11*). Typical solutions to combat segregation driven by this understanding have fallen into two classes: change the particles or change the process. Changing the particles may involve controlling interparticle adhesion (*12*) or balancing the differences in size and density. Changing the process may involve geometrical changes (such as adding internal obstructions called "baffles") or operational changes (such as varying the tumbler speed).

These systematic studies have led to interesting results on the process side. For example, small particles need time to migrate through the flowing layer; thus, if the flow is interrupted before the particles have percolated to the bottom of the flowing layer, the particles do not segregate completely and segregation can be prevented. This relatively simple observation can be applied to devise systems that counteract segregation.

McCarthy and co-workers have implemented this approach using the concept of a "zigzag chute" (*6*). Imagine heavy and light particles flowing down a chute made up of "zigs" that are downward and rightward and "zags" that are downward and leftward. Heavy particles drift downward in the zig portion and end up lower in the flowing layer, but become the upper portion of the flowing layer in the subsequent zag

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portion of the chute, thus thwarting demixing. The idea is reminiscent of droplets in zigzagging channels aimed at generating chaotic mixing in the drops (*13*).

Extensions of the zigzagging idea have practical consequences. Baffles have long been used in mixing tumblers, but were designed by trial and error. Usually, short baffles were attached to the outer wall of the container (see the second figure, left). In fact, the best mixing is achieved with long internal baffles (see the second figure, right) (*6*).

Physical understanding, computational and theoretical approaches (*14–16*), and experimental capabilities (*17*) are now sufficiently mature so that mixing or demixing can be designed into a system with a reasonable probability of success. The next challenge is extending the ideas to three dimensions. Recent theoretical work on mixing a single class of particles in three-dimensional tumblers (*18*)—a far simpler case than mixing two classes of particles—suggests an explosive increase in the richness of problems that may be encountered when tackling mixing and demixing of granular materials.

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ECOLOGY

Green with Complexity

Predators, by affecting prey behavior, can change both plant diversity and productivity in an ecosystem.

Shahid Naeem

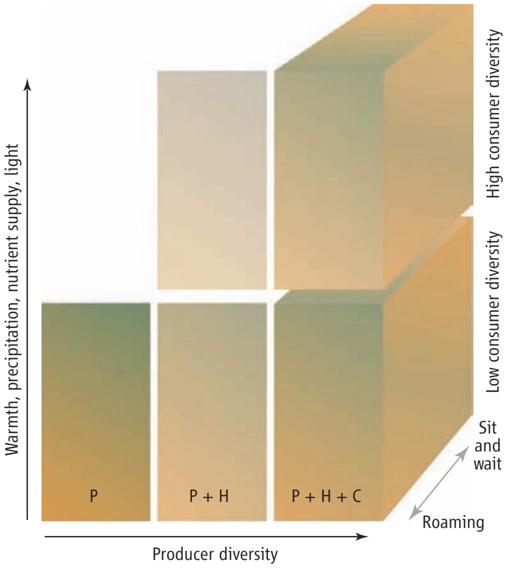
Why the sky is blue is a matter of basic physics, but why land is green is a much trickier question. The obvious response is that land is green because it is covered with plants. This answer, however, raises the question of why land is covered with plants in the face of omnipresent herbivory, which in turn raises the question of why herbivory is omnipresent in the face of omnipresent carnivory? Why land is green, or what governs primary productivity, is one of the most basic yet astonishingly complex questions in ecological research. Like a Russian matryoshka doll, each answer uncovers another question. On page 952 of this issue, Schmitz (*1*) adds to the complexity; given omnipresent carnivory, he finds that behavioral traits affect greenness. This result has profound implications for ecological and environmental research.

Before the 1960s, the question of greenness was largely the domain of ecologists who paid little heed to biodiversity. At its simplest level, greenness measures the density of autotrophs like plants and algae that use solar energy to turn inorganic matter into organic matter. This primary productivity is usually cited in grams of carbon fixed per unit area per year.

The yin to this yang is consumption by heterotrophs that consume and cycle organic matter back to its inorganic constituents. All ecosystem functions, including primary production, decomposition, nitrogen mineralization, nutrient cycling, and energy flow, are driven by the balance between autotrophy and heterotrophy. Primary production, because it is the starting point in ecosystem function, is more intensely studied than other ecosystem functions.

At present, terrestrial global primary production clocks in at 59.22 petagrams (10^{15} g) of carbon fixed per year, almost a quarter of which is appropriated by humans as food, biofuel, and building materials (*2*). Not surprisingly, the principle determinants of greenness were considered to be climate and geography, with animals and microorganisms playing a minor role. But Hairston *et al.* suggested that there was another layer to the question (*3*, *4*). They argued that herbivory should reduce the green world to a barren one, were it not for carnivory.

Although Hairston *et al.* dramatically expanded the complexity of the question of greenness, even deeper layers were unmasked in the 1990s when researchers discovered that biodiversity could also influence greenness. Trophic levels ignore biodiversity, grouping species into layers with producers on the bottom, then primary consumers, secondary consumers, and so on to the top, with each level only about 10% of the biomass of the level below it.



Hunting green. The greenness of ecosystems (rectangles) varies according to abiotic factors such as warmth, precipitation, nutrient supply rates, and light (vertical axis), but other influences are at work. Greenness in a system with only plants (P) is reduced by herbivory (P+H), but carnivory (P+H+C) restores greenness by suppressing herbivory. Increasing producer diversity (from left to right) can increase greenness. High and low levels of consumer (herbivore and carnivore) diversity can also affect greenness if diversity improves the efficiency of one level's exploitation of another. Schmitz suggests that carnivore behavior, in particular its hunting mode, adds a new dimension to ecosystem greenness (the rightmost rectangles become blocks). The degree to which carnivores roam or sit and wait for prey affects herbivore impacts on greenness.

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