Summary

Granular materials such as sand, rice and coffee beans are so common that we hardly ever realize how unique their properties are. Who marvels at the fact one can walk on a dry sandy beach? Who will notice the surprising fact that we can tune the rapidity and thickness of the stream of coffee beans into the grinder, simply by holding the bag differently? Who will find it surprising that a jar of rice can always contain a little amount of extra rice, if you shake the jar a little?

Granular materials are also encountered outside of the kitchen: the aluminum alloy of which the cover of your mobile phone is probably made, is made by melting a well mixed collection of – indeed – small grains of different metals. The stick-slip motion of earthquakes, and the development of snow avalanches are closely related to the processes that occur in a collapsing sand castle.

Moreover, granular materials are part of an even larger class of materials called disordered materials: disordered collections of macroscopic particles, such as mayonnaise, toothpaste and shaving foam.

Disordered materials, and with them granular materials, it can be concluded, fill our everyday life. But despite the omnipresence of these materials, we still do not understand their behavior very well. This is surprising, considering that there are many other types of physical systems with many interacting particles that we do understand. Consider the air we breathe: it is made out of sheer unimaginable number of tiny molecules flying around, yet its properties are well understood, for more than a century already. Substances like water and crystalline solids, other examples of large collections of molecules jiggling around, are also well understood. Then why is the behavior of a small collection of simple sand grains or foam bubbles so hard to model?

The difficulty in describing disordered materials is due to the fact that granular materials interact differently than molecules and atoms that make up gases, liquids and solids. Sand grains for example rub or collide inelastically
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when they come in contact, which means these interactions dissipate energy. Therefore, when not externally driven, a collection of grains comes to rest in a state in which all relevant internal dynamics have ceased. Unlike molecules in ordinary gases, liquids and solids, which always fly, bounce, tumble and vibrate around, the grains in a heap of granular material are stuck -- they are, as one might say, frozen. Therefore, all the ordinary tools physicists have available to describe systems with a large number of particles break down. Finding tools that describe for example the flow behavior, or simply the elasticity of these ‘frozen’ or jammed materials, has proven to be a profound challenge in modern physics.

We study disordered materials experimentally, by studying the flow of spherical glass beads. For this we use a special tool: the split-bottom geometry. Essentially, it is a container with a small rotating disk at the bottom; hence the name ‘split-bottom’. Grains are poured into the container, and the disk is rotated. The disk drags along the particles, and flow is thus induced. The split-bottom setup is a useful tool to study granular flows, since the rotating disk ‘breaks’ the granular material in a very special way -- very broad flowing zones are created, in which many glass beads participate. It is for such flows that one would like to have a model that for example predicts the flow structure. At the moment such models do not exist.

We study these special granular flows in the split-bottom geometry in several ways: In chapter 2, we look at the rheology of such flows: simply put, the rheology is the relation between the forces applied to the flow and the resulting speed of the flow. In slow flows, grains are mostly rubbing against each other, so friction forces dominate the rheology of the flow. When driven faster, the grains in the split-bottom start to collide at higher speeds and more frequently. At some driving rate, the forces related to these collisions will become more important than the frictional forces between the particles, which are independent of the driving rate. We study this transition, which is observed as an increase in the force needed to drive the flow. We verify rheological predictions of a model, initially devised to predict only flow structure properties of split-bottom flows.

In chapter 3 and 5, we study submersed granular flows, also know as suspension flows, in the split-bottom geometry. The fluid now present between the particles changes the rheology of these granular flows flows in an nontrivial way, but we show we can readily capture this by extending an existing, phenomenological theory for fast granular flows.

Submerging grains is not just a way to change the interactions between the particles. We can tune the index of refraction of the interstitial liquid such that is matches the index of the beads -- our suspension is then transparent. Whereas ordinary, dry, granular materials are opaque, and only their surface can
be observed, in transparent suspensions we can study the flow properties in three dimensions. We discover that the extended rheology model mentioned above also gives the right predictions for the flow structure, mainly in the fast driving limit.

Measuring three dimensional flow structure of a fluid, let alone a dense suspension, is not easy. We devoted a substantial amount of work to develop an experimental setup capable of doing so. This is the subject of chapter 4; we show there that with the instrument we developed, we can now scan suspension flows in great detail, at unparalleled imaging rates.

In chapter 6, we ‘unfreeze’ granular materials by means of very weak vibrations. Again, we study the flow of glass beads in the split-bottom geometry, and find that its rheology is completely modified by the weak vibrations: weak vibrations make even slow, friction-dominated flows rate dependent. Moreover, we discover that weak agitations make new types of granular flow possible that had not been observed before.

In chapter 7 we do an experiment, analogous to tapping a jar of rice to add more grains to it: we study how well controlled taps influence the packing density of two different types of granular materials in a glass tube. We find that there is a limit in which the number of taps does not influence the density anymore -- one cannot keep adding rice grains indefinitely. The control parameter that sets this steady state densities, we find to be related to the energy input that the tap delivers, and not simply its amplitude, as was previously assumed.