AAPT- Omaha-SM11, W35: Granular Materials
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How many boxes will fit in your truck? How much does your box of (cereal, candy, grain) settle during shipment? Can you use only half of the package of dry soup mix, and still have both peas and spice in your soup? How many jelly beans does that giant jar in the drug store REALLY contain? These are the types of questions that studies of Granular Materials address. Study of Granular Materials can help answer these and other questions.

A granular material can be defined as any loosely interacting collection of (usually) solid particles.[1] Depending on the conditions, a granular material can be best described as a solid, or as a fluid, or as a gas, or in some case not adequately as any of these, which makes this both an interesting and difficult field of study.

The behavior of granular materials is something that is encountered frequently in all aspects of everyday life. Some of the situations include grain silos, trash piles, sand & salt that is used for building and on winter roads, snow (as in avalanches), and mixing of various food and medical supplies, such as pharmaceuticals. A granular material would be generally defined as consisting of discrete units of a solid material that neither chemically interact, nor otherwise strongly cohere together. Thus, the arrangement and motion of these materials is neither that of a solid (in which the various parts are tightly bound together) nor that of a fluid (in which the parts may easily flow over & around other parts). The size of the particles, per se, is not important -- the phenomenology is similar with very fine grains (such as powders) and with rather large 'grains' (such as cannonballs). The possibility of using various sizes of grains allows for some interesting research proposals covering several length scales. For many experiments the size of the container needs to be 'large' compared to the grain size (typically a factor of 100 could be considered as 'large'), so that end effects are indeed restricted only to the ends. This of course means also a large number of particles – easy with things like sand, less so with things like marbles (100^3 marbles can be quite massive!)

Granular Materials is an area of study in physics that, while it has many important applications, is poorly understood on a fundamental level, and has become a recent area of much interest.

From the theory side, one can most easily model systems that are mono-disperse (contain only one size, or one type, of grain), and that are spherical. This is the one thing that is notable about nearly all the research that has been presented about granular materials: spherical (or occasionally cylindrical) particles are used, of a single type and size; even when mixtures are studied, the mixtures will be of spherical particles (typically ball bearings or glass beads). Thus, the experimental data is taken on spherical particles. This makes for a nice research package, but leaves much lacking in terms of applications. Very few real-life materials that are used are both mono-disperse and spherical. (However, software, such as LAMMPS[2] is available to model spherical particles.)

Among the properties of interest (both pedagogically and practically) are mixing (i.e. how does one get a uniform mixture of two or more materials), segregation (having made a mixture, will the particles separate, under what conditions, and by what property, such as size, shape, density, etc.), packing fraction (how much of the available space is actually occupied by the granules) and angle of repose (what is that maximum stable angle for a pile of the material). The angle of repose is also quite useful for characterization of the materials, in that it depends on such things as friction and particle shape. Of considerable interest is the flow of the particles, and in particular jamming, which occurs as flow ceases; jamming can be studied for both 'solid' granules, and for those that are not really solid, such as emulsions or suspensions of bubbles in a fluid. One can also perform measurements of the various properties that one considers in Condensed Matter studies, such as electrical resistivity, heat flow, and sound propagation. While much of the granular behavior can be modeled using fluid dynamics, there are two major differences: (1) There is no 'pressure head' as one would have in a container of fluid. As the forces are exerted 'out' as well as 'down', unjammed granular materials tend to have a constant rather than a decreasing flow rate – objects such as grain silos tend to explode, and not typically at the base. (2) The (thermodynamic) temperature is not well-defined (or rather there is ongoing discussion as to the best definition – temperature as measured by a thermometer is MUCH below the functional temperature for dynamic behaviors (macroscopic granules do not obviously oscillate or change position spontaneously), though the functional definition of granular temperature as the 'average kinetic energy' of moving particles can be quite useful.

There is such a broad parameter space available that one can use the study of granular materials as a simple pseudo-cookbook exercise, as a short- or long-term inquiry experience, or in fact as the basis for an entire materials course -- which is done at NEIU at two levels – Physics 110: Honors, a general education course, and Physics 361: Materials I (Thermal & Mechanical Properties), which focuses specifically on studying Granular Materials.

Extended or advanced studies can include such things as pattern formation that occurs when a granular collection is vibrated (typically from below), force chains between the granules (which leads to clever imaging techniques), and the rotating drum, in which segregation among non-mono-disperse collection may occur both radially (well understood) and longitudinally (NOT well understood). Students doing experiments on granular materials are quite likely to be doing something that has not ever been measured previously, depending on the particles chosen for study.

A final aside – think carefully about what type of granules you might want to use, and your student audience. Foodstuffs provide the greatest variety of size, shape & texture, and these are readily available and inexpensive; however, the mono-dispersivity for many of these tends to be not as good as with manufactured materials, and these change over time (including damage from being used) and can attract unwanted visitors into the lab (especially if your students are not very neat). Highly monodisperse plastic or metal balls can become quite expensive (and really round things DO roll and can be a tripping hazard). Simple sand is probably the best starting point, and something like 'cactus soil' is actually fairly monodisperse, and one can get a 'large' number of particles at a very reasonable cost.

1.) See for example "Pattern Formation in Granular Materials" by Gerald R. Ristow, (Springer-Verlag, 1999) or "Disorder and Granular Media" by D. Bideau & A. Hansen (ed.) (North-Holland, 1993).

2.) http://lammps.sandia.gov/

Text adapted from various research proposals & reports.

Granular Materials for Advanced Labs
Module of Workshop W35, Omaha/SM-11

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BASIC PROPERTIES:

Angle of Repose

Pouring, Flow & Jamming

Packing Fraction & Settling

Mixing & Segregation

MORE ADVANCED PROPERTIES:

Contacts, Interparticle Forces, and Force Chains

Cratering (Dynamic introduction of an 'intruder' particle)

Granules in Motion I: Liquid-like Flow

Granules in Motion II: Vibrated Materials: Liquid-like & Gas-like phases & Patterns

Rotating Drum Experiment (Radial & Longitudinal Segregation)

Propagation through the Collection (Sound, Heat, Electric Conductivity)

OVERALL CONSIDERATIONS:

How do the various properties vary with particle size, shape, density, surface friction, interstitial fluid, and on whether the collection is mono-disperse, bi-disperse, or poly-disperse.

Good References:

"Pattern Formation in Granular Materials", Gerald Ristow
"Granular Patterns", Igor Aranson & Lev Tsimring
"Disorder and Granular Media" by D. Bideau & A. Hansen (ed.)

The Physics of Granular Materials is a very active area of investigation, since their behavior almost classifies them to be a separate 'state' of matter (distinct from the states we usually discuss, such as Solid/Liquid/Gas/Plasma). When at rest, granular materials are much like solids; when in motion, granular materials are much more like a fluid!

Many of the everyday materials we use and encounter would be classified as granular: powders (sugar, salt, flour, ...), 'bulk' foods (beans, nuts, coffee, seeds, ...), the dirt we walk on (including piles of gravel, unmixed cement, ...), as well as seemingly non-uniform materials (such as cans of mixed nuts).

To a large degree, the properties of the granular materials depend on their surfaces -- the friction and smoothness, as well as anything that is in the "interstices" (the spaces between the grains – such as water, air, …). The properties are usually less dependent on size and density, unless we are making comparisons, or using mixtures of two or more types of materials; however, the particle shape IS important (sphere, cube, cylinder, etc.).

The goal of this exercise is to study, in a semi-quantitative manner, some of the properties of everyday granular materials, including stacking ('angle of repose'), flow, packing and settling; we could also investigate mixing and segregation ("unmixing").

Please TRY not to mix the various types of materials, accidentally, and please don't mix 'foods' with 'non-foods'!

(Partial) list of available granular materials:

- Apple Jacks (cereal "O's" like Cheerios)
- Rice (various kinds, as well as mixtures)
- Sand (of various sizes)
- Beans & Legumes (dry)
- Nuts (shelled & not) (mixed and unmixed)

O.) MATERIALS

Pick at least 4 different materials that you will use. In the data table, describe their properties, including **approximate** grain size, weight, roughness, symmetry, uniformity, etc. Try to pick some that have similarities (such as being round, or flat), and some with clear differences (in size, shape or density).

I.) ANGLE OF REPOSE

When a granular material is put into a pile, the friction between the grains limits the height of the pile, for a particular width of the base; this height-to-width ratio is different for each type of material. The stacking of the grains is typically characterized by the maximum stable angle that the pile makes with the horizontal, called the 'angle of repose'. Stack each of your materials, and measure the height & diameter of your pile. (You can use the height/base ratio for comparison, or if you know some trig, you can use these to fine the actual angle.) If you have enough material, try a 'small' and a 'large' pile, to see that the angle of repose is similar for both. Comment on what occurs when you try to add additional material to the pile. Hint: using some type of 'post' for the base makes the width of the pile well-defined.

II.) FLOW

When in motion, a granular material is more like a fluid (liquid) than a solid -- consider what happens during an avalanche, an earthquake, and during the solid-particle flows from a volcano. However, the flow is also more easily stopped, in certain cases, than is a liquid flow. Since each individual particle is a solid, the particles can get caught in a relatively large opening, and make an arch, which will support the remaining mass. We will try this in funnels of different sizes & shapes.

Take three different size (diameter) &/or shape funnels; describe the funnels on your data table (a sketch works well). Try pouring your granular materials through them -- try pouring 'slow' and 'fast', and record what occurs. How does the occurrence of the arch depend on the relative size of the grain to the funnel? How does the material flow -- does it all flow together, or does it make a hole through the center?

III.) PACKING & SETTLING

One of the important parameters in studying granular materials is called the 'Packing Fraction' -- how much of the available space in a container is actually occupied by the solid material of the granules. To measure this properly, we would need to know both the size (i.e., volume) of each granule, and the volume of the container. THEN, we would need to either count the granules in the container, when it is full, or weigh the container full, to find the number of granules -- this could be tedious, though in principle it is not difficult.

Instead of measuring the Packing Fraction, we will measure a related property -- how the material settles, or what we might call the 'Relative Packing Fraction'. This is what occurs with most dry goods -- you may have noted that boxes of cereal or pasta often have a disclaimer something like "This package is sold by weight, not by volume -- some settling of the contents may occur during shipping & handling". Many materials will occupy a relatively large volume when first poured, but then as the package is handled (and some energy is made available for rearrangement), the granules will reorganize into a smaller volume.

Pick 2 or 3 different containers -- if available, you might want to try different shapes, such as cylindrical vs. rectangular. Using your chosen granular material, fill the container up to some level (the actual level you choose may not be important -- somewhere less than 'full to the brim' but greater than ½ full). Record the depth of the granules in the container. Now, shake the container strongly several times. (Again, how many times may not matter -- but you probably want to do the same number of shakes each time.) Record the new depth. Repeat this several more times, to see how the material settles -- if you shake enough, the amount of settling in each round will probably decrease. HINT: use a container that you can cover, so granules do not spew across the room! You may note, as you do this with your different granules, that some materials\shapes will settle a lot, and some will settle very little.

Don't forget to write a conclusion on what you observed -- you probably will want to compare & contrast how different materials behave. Feel free (with proper citation) to compare/contrast your data with that from other groups.

Physics 361: Granular Materials: Expected Lab Exercises Fall 2005

(tentative date of lab)

<<DRAFT: 6/25/05>>

1.) Angle of Repose (I) R 9/1

Measurements of the Angle of Repose of 2-D and 3-D 'piles' of various materials

2.) Angle of Repose (II) R 9/8

Comparison of the Angle of Repose of monodisperse piles vs. that for polydisperse piles (1 type of granule vs. 2 or more types)

3.) Angle of repose (III) R 9/15

Measurement of the Angle of Repose of the same type of material, but for various shapes (possibly different types of pasta)

4.) Packing Fraction R 9/22

What percentage of the volume displaced by a granular material, in a container, is actually (solid) granules?

5.) Mixing & Segregation R 9/29

How can we effectively mix different types of granular materials?
How can we effectively segregate a mixture?

6.) Funnel Flow R 10/13

How do granules flow through a funnel?
How does this depend in such things as neck length, neck & funnel angle, neck & funnel size?

7.) Sound Emitted From & Transmission through Granules R 10/20

What is the noise spectrum of a flowing granular material?
How (or is) sound transmitted through a granular material?

8.) Vibrated Granular Materials/Pattern Formation R 10/27

What happens when pan of a granular material is vibrated?

9.) Rotated Granular Materials/Pattern Formation R 11/3

What happens when a bin partially full of a bi-disperse granular material is rotated?

10.) Cratering R 11/17

What happens when a large 'intruder' particle impacts a granular surface?

11.) Magnetic Granular Materials R 12/1

How does the behavior of granules change if they are magnetic?

DATA TABLE: Granular Materials 06.01

O.) MATERIALS

Describe the materials that you are using:

Material	(Approx.) Size	Shape	(Approx.) Weight (each granule)		

Comments:

I.) ANGLE OF REPOSE

Material	Height	Base Diameter	Ratio, Base/Height	(Optional) Angle of Repose (if you know trig)

Comments:

II.) FLOW

Describe your funnels (size, shape – a figure would be helpful):

Material	Funnel Size	Pour Rate (Slow, Fast, etc.)	Describe Actual Flow	

Comments:

III.) RELATIVE PACKING FRACTION

Describe each shaking 'event' (how many shakes, how hard, etc.)

Material & Container	Initial Height	Height after 1st shaking	Height after 2nd shaking	Height after 3rd shaking	Height after 4th shaking	Height after 5th shaking