Squishy Materials

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Submitted to The Physics Teacher, July 2004

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Key words: complex materials, jamming, granular media
PACS numbers: 01.55, 01.50M, 46.30J

Introduction

Most people do not realize that many substances they use in the kitchen and the bathroom are not simple liquids or solids. Creams, shampoos, toothpaste, and ketchup all have properties of both liquids and solids. This article describes how we teach students about squishy materials, and at the same time expose students to current physics research questions. Unlike some areas of physics, the concepts behind squishy materials are understandable even by beginning students.

For three semesters, we've taught a short unit about complex fluids as part of an undergraduate freshman seminar. Our students had a variety of backgrounds and several of them had not taken a physics course before. While our unit was taught in five class periods of 75 minutes each, portions of our class would be easy to use in high school classes or introductory college classes as part of a single-period laboratory exercise. We have placed on the Electronic Physics Auxiliary Publication Service [1] movies, discussion questions, descriptions of student experiments, examples of lab reports, and links to several research group web sites.

The first goal of our unit is to teach students how complex fluids (such as sand or shaving cream) differ from simple liquids (such as water or honey). The second goal is to expose students to the theory of jamming [2], so that they get a taste of current physics research not normally seen in introductory science courses.

Conceptual explanations of "squishy physics" can be introduced to students without requiring any prior physics knowledge. Before each class the students are assigned a short reading [1] to enable them to participate in the subsequent class discussions. To encourage the students to read, we require them to email us at least two questions about each reading before class. Many of these questions are used to stimulate discussion in class, and those that aren't discussed are answered after class by an email sent to all of the students. After classes in which experiments were performed, the students write short lab reports [1], to encourage them to think about what they had observed, and for us to discover if they had any misconceptions.

We start our unit by introducing the students to Brownian motion. Next, the students do experiments to understand viscosity, and to learn how viscosity influences Brownian motion. We carefully distinguish the concepts of viscosity and density, a common confusion for our students. The students then play with squishy materials, for which the effective viscosity depends on how the material is tested. Squishy materials are followed by experiments with sand, which has some similarities with the previous materials. Finally, we conclude the course with a discussion on the theory of jamming [2], a current theory that tries to explain the microscopic origins of the behaviors of both squishy materials and sand. In this way we connect the properties of these materials back with the ideas of Brownian motion.

Activities and experiments

In this section we describe the experiments the students conducted in the course; the next sections show how these experiments are implemented in our 3 week class.

Brownian motion experiments and activities

First, to simulate 2-dimensional random walks, we give each student a coin. They flip the coin, and turn right for heads and left for tails. Then they take a step. They repeat this several times. The students count the steps needed to reach a specific distance from their starting point.

Second, the students look at microscope slides with polystyrene particles of different sizes (diameter of 0.5 μm and 1.9 μm [3]) dispersed in either pure glycerol [4] or in a glycerol/water mixture. The students make qualitative observations of the Brownian motion to determine the influence of particle size and viscosity [5].

Viscosity and density experiments

The students experiment with three different liquids. We use water, glycerol, and vegetable oil for our three liquids, as they all have similar densities but have significantly different viscosities (Table I). Honey could be used in place of glycerol. Students start by measuring the liquids' densities, by weighing known volumes of each.

Substance	Viscosity η (mPa·s)	Density ρ (g/cm^3)
Water	1.0	1
Vegetable oil	50	~0.92
Glycerol [4]	1500	1.26
Honey	10000	~1.42

Table I. Viscosity and density of regular liquids; note that exact values for all viscosities depend sensitively on temperature [6].

The first viscosity experiment is to time the fall of glass spheres in graduated cylinders filled with each of the liquids [7]. The second viscosity experiment is to time the draining of the liquids from a container. We take a plastic beaker and drill a 1/8" diameter hole in the bottom. The students measure the time it takes for a fixed volume of each fluid to drain from the beaker.

Squishy materials experiments

The students experiment with four different squishy materials (Table II). Each pair of students receives a beaker filled with each substance, another empty beaker, a stop watch, a set of spheres (used before in the falling ball experiments), two microscopic slides, and a spatula. In our class, we let the students freely experiment; in other classes, it may be desirable to explicitly specify what experiments the students should try. The key observation is to notice how easy or hard it is to stir the materials at different speeds.

Sand experiments

The students conduct three experiments.

- they pour sand [8] from a beaker at different angles.
- they tap beakers filled with sand and observe that the level of the sand surface decreases with the tapping.
- they observe the "Brazil nut effect" [9]: they place a steel sphere at the bottom of beaker and cover it with sand. Next, they tap the bottom of the beaker several times against the table. The heavy steel sphere rises to the top of the beaker.

Starting the course: Classical Physics

We start our course with the fundamental themes of microscopic motion: random walks and Brownian motion. A random walk is one where the direction of motion is random for each step, often also called a "drunken walk". Rather than giving the students beers, we give them coins (*Brownian motion experiments and activities*). This shows them what a random walk is and they all agree that it is similar to the motion of a butterfly or a mosquito. We reinforce this by watching a video clip of Brownian motion [1].

Students suggest many interesting parameters on which Brownian motion may depend: temperature, viscosity, particle size, fluid or particle density, and particle surface. The Stokes-Einstein formula shows that the diffusion constant D depends only on a few of these parameters:

$$D = k_B T / 6\ \pi \eta R,$$

with k_B = Boltzmann's constant, T the absolute temperature, η the bulk viscosity, and R the particle radius. The mathematics behind diffusion is well beyond our course, so we don't explicitly discuss the Stokes-Einstein formula. Instead, we have the students directly observe Brownian motion themselves to qualitatively understand two of these parameters (R and η), as described above under *Brownian motion experiments*. Movies of these are available [1].

In order to get more familiar with the notion of viscosity the students perform the *viscosity and density experiments* with the liquids listed in Table I. Students measure the liquids' densities and see that they are reasonably close. Next, students time the fall of spheres through the liquids. The time for the fall varies dramatically, far more so than the densities vary, and gives the students an idea of the influence of viscosity as the internal resistance of a liquid to flow [10]. This concept is reinforced by the second viscosity experiment, timing the draining of the liquids from a container. Again, the answers vary widely between the liquids, more so than could be accounted for by density differences [19]. A quick discussion after the experiments helps clarify the difference between density and viscosity: density measures how much stuff there is in a given volume, whereas viscosity is analogous to friction between different parts of the liquid.

Squishy Materials

The students next experiment with squishy materials that do not have well defined viscosities. We chose to use unfamiliar substances (Table II, our choices in bold).

Substance	Type & Behavior
light mineral oil [11]	Regular liquid: The viscosity is constant with mixing rate [12]
vegetable oil	
glycerol [4]	
bentonite clay and water [13]	Bingham liquid: The mixture has a yield stress (Fig. 2). This means that there is no flow for weak forces; for strong forces, viscosity is constant with mixing rate.
shaving cream	
ketchup	
xanthan gum and water [14]	Shear-thinning liquid: The viscosity decreases with mixing rate.
mayonnaise	
small acrylic beads and water [15]	Shear-thickening liquid: The viscosity increases with mixing rate (Fig. 1).
sand and water	
corn starch and water	

Table II. Squishy materials exhibiting "regular" and complex behavior. The substances we use in our class are in bold. Sources for unusual materials are provided as referenced.

In our class, we've let the students design their own experiments to test the properties of the materials (see above, under *squishy materials experiments*). Students usually start by dropping spheres into the substances, given the success they had previously with dropping balls in viscous liquids, but these experiments are generally unrevealing. They next try stirring the substances, which is the key experiment they need to do. Shear-thinning liquids are easier to mix quickly; shear-thickening liquids are harder to mix quickly. (Corn starch and water is perhaps the most dramatic example: at the right concentration of corn starch, a mixture can be rolled around in your hand like a ball of soft clay, but will then flow like a liquid when you cease rolling it [Fig. 1]). For a Bingham liquid, a spatula can stand up at a slight angle, as shown in Fig. 2. Students frequently interpret this as an extremely high viscosity, but then find it quite puzzling that the mixture is easy to stir by hand.

Fig. 1. A corn starch-water mixture can be rolled around in your hand like a ball of soft clay (left), but will then flow like a liquid when you cease rolling it (right).

The students try to figure out the composition of the materials. We have them wear latex gloves, not for safety (all of the substances are benign to touch) but more to encourage them to play freely with the materials. The acrylic spheres/water mixture and bentonite/water mixture feel "grainy," while the xanthan gum/water mixture feels "slimy." Some students dry the materials out on the microscope slides, which leaves an intriguing residue in some cases (such as the acrylic spheres in water). Some students shear the materials between two microscope slides.

Fig. 2. A metal spatula stays inclined in a mixture of Bentonite and water, suggesting it is an elastic material; yet when stirred by hand with the spatula, it stirs almost as easily as water.

The last experiment most students perform is pouring the substances from one beaker into another. Bingham liquids don't flow until the beaker is tilted a fair bit (due to their yield stress), and shear-thickening liquids flow, but quite slowly.

After they write down their observations we discuss the behavior of the substances and reveal what substances they tested. We use their observations to give conceptual definitions of the terms shear-thinning, shear-thickening, and yield stress. Some students may wonder about the viscosities of these substances, and how they can be quantified given these changing properties, which can lead to a discussion of more sophisticated methods used by physicists and engineers to study properties of complex materials [16,17].

What keeps ketchup in a bottle? Why is it easier to mix the acrylic beads/water mixture when it is mixed slowly? Answers to these questions are difficult but we put forward a few ideas and listen to the response of the students. Here we try to set the stage for the later discussion of jamming. For ketchup, the tomato fibers form a network. This network is what prevents ketchup flowing easily out of the bottle and it results in ketchup having a yield stress – just like the bentonite/water mixture. Is there something similar in the acrylic beads/water mixture? If we mix the acrylic beads/water mixture slowly, the grains are coated with water. When the beads are lubricated, they slide passed each other. When we mix them faster, the grains come in contact with each other creating higher frictional forces between them and they *jam*!

Jamming and Sand

The idea of jamming is fairly simple: for example, consider shaving cream foam. It can make a stiff pile, which will support some weight (a small piece of paper, for example). However, if you add water, eventually at some point it forms a bubbly puddle. The theory of jamming tries to explain how the foam goes from a jammed state (where it can support weight) to the unjammed state (where it flows like a liquid) [2].

A pile of sand is a simple example of a jammed structure. Therefore, to gain more insight into jamming on the macroscopic scale and to learn about the unusual properties of granular media, the students perform more experiments with regular sand [8] described previously. The sand experiments allow students to begin connecting mesoscopic properties of materials to macroscopic phenomena in a conceptually simple way.

The first experiment introduces the notion of angle of repose – the lowest angle at which the top surface of sand starts to flow. We want them to note that sand forms piles, not puddles, and to think about how friction between grains holds them together into the pile. The second experiment demonstrates that sand can compact when its container is tapped, which allows the sand grains to find more stable and denser mesoscopic configurations.

Finally, they perform the "Brazil nut" experiment [9]. This behavior is similar to the observation that in a box of mixed nuts, the big Brazil nuts are usually at the top. We encourage the students to try to come up with a mesoscopic explanation for this puzzling experiment. Why would a heavy, dense steel sphere move up in a tapped container of sand? The simplest answer is that when the beaker with the sand is tapped, the sphere moves a little bit further up than the sand particles. Since there is a void behind the steel sphere, the smaller sand particles easily fall into this void. Thus the sphere can't settle in its previous position [1,9]. The sphere settles a little bit higher with each tap, and with many taps the sphere slowly rises to the top.

We use their experiments as a basis for discussing the theory of jamming in our final class period. We start with the students reflecting back on Brownian motion in regular liquids. We discuss the microscopic behavior of the familiar states of matter: gases, liquids, and solids. Our students start with reasonably correct ideas, and to reinforce them, we perform the following activity. First we tell them to move around freely just like molecules in a gas. Next, we tell them that they (as a group) can move only within a given area. Thus, their motion is limited and often depends on the motion of their neighbors, similarly to a simple liquid. Finally, we tell the students to stand in one spot and imagine that the temperature has dropped below 32°F. All of them start shaking and jumping roughly in one spot thus portraying molecules or atoms in a solid.

In squishy materials something must be different and that difference may relate to the complex macroscopic behavior. For example, in foams the bubbles are mostly stuck in the same place; the same is true for particles in a sand/water mixture.

To facilitate this discussion, the pre-class reading is a short article about the theory of jamming [2]. Due to the technical nature of the article, we provide a glossary of terms to accompany the article [1]. The key idea behind jamming theory is based on observations of granular materials: in a pile of sand, the inter-particle forces are not all the same, but vary widely. In particular, a few particles feel extremely large forces, and support much of the weight of the pile. Current research suggests that these force-bearing particles are arranged in chains, which is strongly suggested by two-dimensional experiments (see Fig. 3). The particles in force chains are jammed and it requires an external force (a tap for instance) to make them move and unjam. The article introduces these ideas, which we clarify in class.

Next we discuss the possibility that tomato paste in ketchup may jam similarly to macroscopic grains of sand. Perhaps the existence of a yield stress in Bingham liquids may be due to the jamming of particles; perhaps the shear-thickening liquids are due to mixing-induced jamming. Furthermore, perhaps regular window glass may be a jammed material as well. These are speculative but key ideas of jamming that are yet to be verified [2]. By having the students read the article before class, the discussion is reasonably smooth, and thus the students can see the excitement of questions that are currently being asked in the physics community. Moreover, this allows us an opportunity to discuss how our own work on jamming and complex fluids relates to what they learned in class [18].

Fig. 3. Left: Photoelastic disks show force chains when viewed between crossed polarizers. Compressed disks are birefringent, and thus appear brighter. The configuration of disks in the old game "Risky" also suggests force chains.

Conclusions

The students liked our unit and were surprised how fun physics could be. They especially enjoyed the hands-on experiments they did nearly every class. In surveys that they filled out at the end of the unit they emphasized how important it was to perform the experiments and discuss the results in the class. Overall, the students had a sense that the world is more interesting than they had suspected, and that some intriguing phenomena are present in their everyday lives. Furthermore, we gave them a taste of the excitement of physics research and unanswered scientific questions that they don't normally see in their introductory science classes.

We close with a quote from Victor Weisskopf [20]:

> The study of open scientific frontiers where unsolved fundamental problems are faced is, and should be, a part of higher education. It fosters a spirit of inquiry; it lets the student participate in the joy of a new insight, in the inspiration of new understanding.

Acknowledgements

P. Habdas and D. G. Lynn were supported by a grant from the Howard Hughes Medical Institute. E. R. Weeks was supported by a grant from the NSF (CAREER: DMR-0239109). We thank S. Franklin for a careful reading of our manuscript.

References:

[1] We intend to place additional materials on the Electronic Physics Auxiliary Publication Service. Copies of these materials and associated movies can be viewed at www.physics.emory.edu/~weeks/squishy/

[2] A. Liu and S.R. Nagel, Nature **396**, 21 (1998).

[3] A set of colloidal particles can be purchased from Bangs Labs (www.bangslabs.com) or from Duke Scientific Corporation (www.dukescientific.com)

[4] Glycerol, 99+%, 1 L – about $24 (Fisher Scientific No.: 31549-K2).

[5] Polystyrene particles can be expensive, so if desired, simpler experiments allowing the students to see Brownian motion could be performed. A small amount of milk can be mixed with water (ratio 1 drop of milk to 10 drops of water) and looked at with low power (10 – 40×) microscopes that can be found in typical biology classrooms. Students can watch the Brownian motion of fat globules.

[6] For example: a change of temperature of water from 30°C to 20°C results in about 20% drop in viscosity. To learn more visit: www.hbcpnetbase.com (CRC Handbook of Chemistry and Physics, 84th Edition).

[7] A set of spheres can be obtained from Small Parts Inc. (www.smallparts.com) for under $25.

[8] Regular sand can be purchased from Home Depot - $10 a bag.

[9] H.M. Jaeger, S.R. Nagel, and R.P. Behringer, “Granular solids, liquids, and gases”, Rev. Mod. Phys., **68**, 1259 (1996). This article discusses many phenomena in granular media including the “Brazil nut effect”.

[10] While density does play a role (in changing the buoyant force on the sphere), with glass spheres this secondary affect doesn’t change the results by much, as $\rho_{\text{glass}} \approx 2.6$ g/cm^3 is much larger than the density of all of the liquids. In a more mathematically rigorous class, the velocity can be measured and compared to the net force to determine a value for viscosity, using the Stokes Law: $F_{drag} = 6\pi\eta Rv$.

[11] Light mineral oil, 1 L – around $40 (Fisher Scientific No.: MX1561-1).

[12] Regular liquids are often called “Newtonian fluids” after Newton, who found that their viscosity is independent of the speed at which the fluid is sheared.

[13] Bentonite 500 grams - $11 (Fisher Scientific No.: A15795-36).

[14] Xanthan gum 100 grams - $17 (Fisher Scientific No.: 96002180). Xanthan gum is a common food thickener.

[15] Acrylic beads, Grove Tech Sales, Albany, GA. Tel.: (229) 883 7279. 50 pound bag – $18. See also www.rodeco.com for a wide selection of glass spheres.

[16] Richard A. L. Jones, “Soft Condensed Matter”, Oxford University Press 2002.

[17] F. A. Morrison, “What is rheology anyway?,” online on *The Industrial Physicist* at: www.aip.org/tip/INPHFA/vol-10/iss-2/p29.html

[18] See our web page at http://www.physics.emory.edu/~weeks/lab/

[19] Density plays a role in determining the hydrostatic pressure within the draining container, which causes the fluid to flow out, but the main influence on draining time is the viscosity.

[20] V. F. Weisskopf, “The privilege of being a physicist,” *Physics Today* **56**, 48 (February 2003).