Squishy Materials

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Most people do not realize that many substances they use in the kitchen and the bathroom are not simple liquids or solids. Everyone is familiar with three states of matter: solids, liquids, and gases. However, creams, shampoo, toothpaste, and ketchup all have properties of both liquids and solids. This paper describes demonstrations and laboratory exercises[1] that show intriguing properties of squishy substances, defined as materials that are not unambiguously solid, liquid, or gas. Unlike some areas of physics, the concepts behind squishy materials are understandable even by beginning students. Squishy physics can be used to show physics questions arising from everyday life and to convey the excitement of current research.

The activities described in this paper have two goals. The first goal is to show how complex fluids (such as sand or shaving cream) differ from simple liquids (such as water or honey). The key difference is that the effective viscosity of a complex fluid strongly depends on how it is measured. The second goal is to get students to think about how the microscopic properties of a sample relate to the macroscopic properties. We do this by exposing students to the theory of jamming[2] so that they get a taste of current research not normally seen in introductory science courses. At Emory, we have incorporated the ideas in this article as a short unit within an undergraduate freshman seminar that covers several topics in science. These activities could easily be adapted for other introductory physics courses, and the treatment can be conceptual or quantitative.

Fig. 1. A cornstarch-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).

Regular Liquids and Squishy Materials

The unique properties of squishy materials are best understood by comparison with those of regular liquids, specifically viscosity and density, two concepts commonly conflated by students. We show our students liquids with similar densities but widely differing viscosities; suggestions are listed in Table I. Depending on the class, these liquids could be passed around during a discussion or students could conduct quantitative experiments (described in Ref. 1).

Squishy materials typically do not have a well-defined viscosity. To learn this in our class, students build towers of shaving cream, stir cornstarch and other solutions, and pour ketchup, although these also serve as good demonstrations. Short movies of these demon-

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Table I. Viscosity and density of regular liquids; note that exact values for all viscosities depend sensitively on temperature.[3]

Substance	Viscosity η (mPa·s)	Density ρ (g/cm^3)
Water	1.0	1
Light mineral oil[4]	20	0.84
Vegetable oil	50	~0.92
Glycerol[5]	1500	1.26
Honey	10,000	~1.42

Table II. Examples of squishy materials. The substances we use in our class are in bold; we prefer to use materials unfamiliar to the students. Sources for unusual materials are provided as references. These materials are all safe to touch, but we have our students wear latex gloves to encourage them to play freely with the materials.

Type	Substance
Shear-thickening liquids	**small acrylic beads and water[6]**
	sand and water[7]
	cornstarch and water (see Fig. 1)
Shear-thinning liquids	**xanthan gum and water[8]**
	mayonnaise
Bingham liquids	**bentonite clay and water[9]** (see Fig. 2)
	shaving cream
	ketchup
Granular materials	**sand**
	rice

strations are on the web.[1]

We give our students beakers filled with different substances (Table II) and spatulas so they can stir the substances as a qualitative probe of viscosity. We also give them a regular liquid from Table I as a comparison. The other substances fall into four categories, each with distinct properties.

Shear-Thickening Liquids: These have a low apparent viscosity when mixed slowly, but the viscosity grows dramatically when mixed quickly—in other words, the liquid "thickens" when shear is increased. Cornstarch is perhaps the most dramatic example: A mixture of ~50% by weight mixed with water 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). This is a good demonstration of a material with both liquid-like and solid-like properties under different circumstances.


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.

Shear-Thinning Liquids: The opposite of shear-thickening liquids, these have a higher viscosity when mixed slowly and are easier to mix quickly. Xanthan gum[8] is a particularly interesting case; it is a polymer that is a common food thickener and is found in salad dressing, for example. Salad dressing pours easily when the bottle is tilted but appears fairly viscous when sitting in a small amount on a plate, forming a thick layer. At high concentrations (~4% by weight, mixed with water) a xanthan gum mixture in a beaker appears as elastic as Jell-O when the beaker is lightly tapped, yet it still pours quite easily.

Bingham Liquids: These possess a yield stress, meaning that when the applied force is small enough the material behaves like a solid. For example, a spatula can stand up at a slight angle in a Bingham liquid, 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. Once the yield stress is exceeded, a Bingham liquid has a viscosity that is mostly independent of

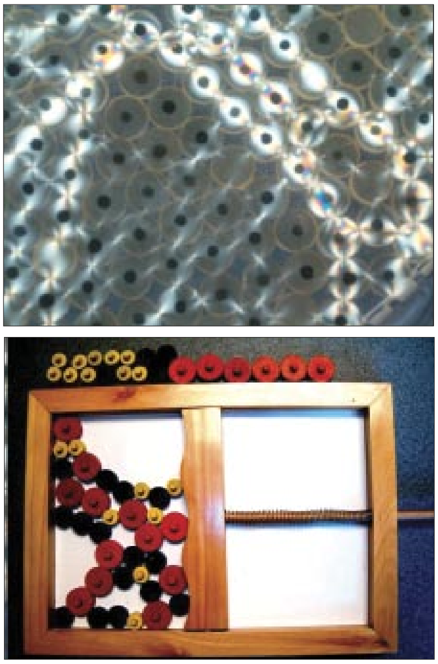

Fig. 3. Top, photoelastic disks show force chains when viewed between crossed polarizers. Compressed disks are birefringent and thus appear brighter. The configuration of disks in the old game "Risky," (also sold as "Booby-Trap") bottom, also suggests force chains.

shear rate. Ketchup is a common example of such a material.

Granular Materials: These have properties similar to Bingham liquids but are dry and do not have a well-defined viscosity under any conditions.[10] Static friction between grains can hold a spatula upright in a granular pile. It is intriguing that sand can have fluid-like properties (when it is poured out of a container, for example) yet is composed only of solid grains, unlike the other squishy materials.

For each of the materials, students primarily need to observe that the materials' resistances to stirring—in other words, their effective viscosity—can depend strongly on how they are stirred (fast or slow, for example). If time allows, students can try other experiments with these materials.[1] In a more advanced class, the qualitative observations could lead to a discussion of more sophisticated methods used by physicists and engineers to measure the viscosity and other properties of complex materials.[11,12]

If you have time, other experiments demonstrating unusual behavior in granular material can be performed.[1,10] A particularly useful demonstration showing the solid-like properties of sand was demonstrated a few years ago in *TPT*.[13] Fill a bottle with uncooked rice; it is important that the neck of the bottle be smaller than the circumference of the rest of the container. (An empty water bottle works well.) Plunge a pencil into the bottle, and then lift up slowly—often the bottle will come up with the pencil. If you twist the pencil, however, it is easily removed from the bottle.

Microscopic Origins of the Behavior

We finish by having students consider microscopic explanations for the observed behaviors. In particular, solid-like properties may result from microscopic networks that span the material. For example, in the demonstration with the bottle filled with rice, the phenomenon is due to "force chains." In a pile of sand or a container full of rice, 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 a sand pile or help transmit the weight of the rice to the walls of the bottle. Current research shows that these force-bearing particles are arranged in chains, which is strongly suggested by two-dimensional experiments (see Fig. 3).[10] The forces are transmitted from one particle to the next through the mechanism of static friction. With the demonstration of the bottle filled with rice, having the bottle filled nearly to the top helps facilitate the demonstration by allowing shorter force chains to bridge from the pencil to the neck of the bottle.[10] This is similar to breakfast cereal jamming when being poured out of a narrow opening in a box of cereal.

A similar network explanation applies to a shear-thickening liquid. For example, if we mix the acrylic beads/water mixture slowly, the grains are coated with water. When the beads are lubricated, they easily slide past each other. When we mix them faster, the grains come in contact with each other, creating higher frictional forces between them, and they jam. In a shear-thinning liquid or a Bingham liquid, typically the networks are weakly connected by chemical bonds between the molecules. The networks are tenuous in an undisturbed material and break when force is applied, allowing the material to flow more easily.

In our class, we make this discussion of networks slightly more technical by teaching the students concepts behind the theory of jamming. A current theory suggests that the solid-like properties of a wide variety of squishy materials may have common origins in similar networked structures. The key idea behind the theory is that the networks of force chains seen in granular materials may be present in some form in other squishy materials. Currently it is not clear if this is true in detail, or if the solid-like properties of different squishy materials are only macroscopically similar and microscopically different.

To facilitate a class discussion, we assign a pre-class reading of a short article about the theory of jamming. Due to the technical nature of the article, we provide a glossary of terms to accompany it.[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.

Conclusions

Learning about squishy materials gives students a sense that the world and phenomena present in their everyday lives are more interesting than they suspect. Students can learn about these materials either through demonstrations or through hands-on experiments. It is interesting that the properties of squishy materials may be viewed in terms of one theory, the jamming theory. By introducing jamming theory, students get a taste of the excitement of physics research and see unanswered scientific questions that they don't normally see in introductory science classes. We close with a quote from Victor Weisskopf:[14]

> 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.

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2. A. Liu and S.R. Nagel, "Jamming is not just cool any more," *Nature* **396**, 21 (1998).
3. 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 http://www.hbcpnetbase.com (*CRC Handbook of Chemistry and Physics*, 84th Edition).
4. Light mineral oil, 1 L – around $40 (Fisher Scientific No. MX1561-1).
5. Glycerol (99+%), 1 L – about $24 (Fisher Scientific No. 31549-K2).
6. Acrylic beads, Grove Tech Sales, Albany, GA; 229- 883-7279. 50-pound bag – $18. See also http://www.rodeco.com for a wide selection of glass spheres.
7. Regular sand can be purchased from Home Depot –$10 a bag.
8. Xanthan gum, 100 grams – $17 (Fisher Scientific No. 96002180).
9. Bentonite, 500 grams – $11 (Fisher Scientific No. A15795-3 6).
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