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The Soft Matter Kitchen: Improving the accessibility of rheology education and outreach through food materials

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COLLECTIONS

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ABSTRACT

Foods can serve as a universal route for the understanding and appreciation of rheologically complex materials. The Soft Matter Kitchen is an educational outreach project started during the COVID-19 pandemic that leverages food recipes and experiments that can be carried out at home to discuss concepts in soft matter and rheology. This educational article showcases two representative outreach demonstrations developed by The Soft Matter Kitchen with detailed instructions for reproduction by a presenter. The first demonstration introduces the concept of complex materials to clarify the definition of rheology by comparing the flow behavior of whipped cream and honey. The second demonstration introduces the concept of material microstructure affecting material properties and macroscale behavior using a simple experiment with cheesecake. By grounding the presentation of this knowledge in food materials with which the audience likely already has experience, the goals of this project are to accelerate the understanding of rheological concepts, increase awareness of rheology in everyday life, and promote the development of intuition for rheologically complex materials.

I. INTRODUCTION

Soft matter is a broad category that includes polymers, colloids, emulsions, suspensions, and granular materials; these types of materials and others are often referred to as rheologically complex.[1] Rheology can be defined as the study of deformation and flow of complex materials. The field of rheology, then, is very broad and interdisciplinary by nature, and relevant in many areas of science and engineering, including chemical engineering, biological engineering, mechanical engineering, food technology, and beyond. As with many scientific disciplines, accessibility is a persistent concern in the rheology community,[2,3] and soft rheologically complex materials—sometimes referred to as non-Newtonian fluids—have been considered underrepresented in the standard toolbox of engineers as a whole.[4] Several high-quality textbooks on rheology that begin at an introductory level do exist[5,6] but target an audience that is willing to invest in reading a textbook, likely because they are already interested in learning about the field. Educational outreach plays an important role in increasing accessibility to complex scientific concepts and allows one to engage a broad audience with a level of understanding that encourages further curiosity and study. The Soft Matter Kitchen is an educational outreach project that discusses concepts in the fields of rheology and soft materials using food recipes and experiments that can be carried out in one's own kitchen. This educational article showcases adaptations of some of the content produced by The Soft Matter Kitchen over the past two years.

The philosophy behind the development of The Soft Matter Kitchen is that food can serve as a universal route for the understanding and appreciation of rheologically complex materials. In addition, the COVID-19 pandemic-related restrictions created circumstances in which dissemination of knowledge was—and continues to be—more difficult; effective education and outreach highly favor content and experiences that are either compelling in an online format or which can be directly performed in one's own home.[7] Foods are relatable to every community in the world and can be used to demonstrate a huge range of rheological phenomena that are both functional and fun. By grounding the presentation of new knowledge in food materials with which the audience likely already has experience, the intentions of this educational project are to (i) accelerate understanding of rheological concepts, (ii) increase awareness of rheology in everyday life, and (iii) promote the development of intuition for rheologically complex properties. The last goal relates to the development of design practices for these materials;[8,9] helping learners to develop a deeper intuition for rheologically complex materials has been reportedly difficult but would accelerate their integration into an engineering design toolbox.[10]

The remainder of this work consists of two demonstrations that are adapted from content that is currently hosted on The Soft Matter Kitchen website (www.arif.zone/kitchen). These adaptations are given in the form of detailed instructions for a presenter to an audience that is not physically present, though the experimental aspects may be performed by learners in their own kitchens with minimal investment. Alternative configurations of the experiments will be commented on in the case of limited availability of resources and equipment. These presentations are targeted toward high school and undergraduate students interested in science, technology, engineering, and math (STEM) fields that have little-to-no knowledge of rheological concepts, but with at least minor prior knowledge regarding states of matter, fluid properties, and food ingredients. However, the author has also personally found aspects of these demonstrations to be highly useful and well-received when introducing rheology research to interdisciplinary audiences of graduate students, faculty, and industrial scientists.

II. INTRODUCTION TO RHEOLOGY

The definition of rheology—as the study of flow and deformation of complex materials—is notable for how non-useful it is to an uninformed audience; while "flow" and "deformation" hint at the meaning, "complex" is a relatively opaque descriptor of the sorts of materials that are of interest to the rheology community. The following demonstration introduces the concept of rheologically complex materials using two common store-bought food items: honey and whipped cream. The video version of the demonstration that this work adapts is available at youtu.be/XDxy4Krj9u4.

A. Materials

One 250 g can of whipped cream.
One 400 g bottle of honey (Note the vast majority of store-bought honeys are simple, Newtonian fluids; avoid specialty honeys like heather, manuka, and eucalyptus, which reportedly may show non-Newtonian behavior.[11] This behavior was explored in a different Soft Matter Kitchen entry available at youtu.be/No6E53wp490.).
One flat tilt-able plastic surface approximately 35 cm in length.
Two 100 g brass disk weights (or other flat-bottomed weights between 50 and 100 g).
Two small serving dishes.
Two small metal spoons.

B. Procedure

To begin, the audience is reminded of basic and intuitive definitions of fluid and solid states of matter; for this demonstration, the key information is that fluid materials take the shape of their container, whereas solids have their own shape. The audience is then asked to consider whether honey or whipped cream is a more viscous material based on their prior experience, with a reminder that viscosity is defined as the resistance to flow. If possible, it is highly encouraged that the presenter quickly polls the audience; informally, in the author's experience, audiences tend to select honey at a rate of approximately 90%. The presenter then performs two experiments to test which material is more viscous.

(i) Viscosity with a large applied stress

1. On a flat, tilt-able surface, deposit parallel lines of the whipped cream and honey and spread them to wet the surface with each line having an approximately constant height.
2. Place the flat surfaces of the weights in contact with each of the deposited lines at one end.
3. Raise the end of the tilt-able surface that the weights were placed on until both weights begin sliding down (for a 100 g weight, an angle of approximately 15° should be sufficient). Note that depending on the geometry and mass of the chosen weight, direct contact between it and the surface may lead to irregular sliding; if this occurs, a thicker layer of material should be applied).
4. Observe that the weight placed on the whipped cream will slide much more rapidly than the weight placed on the honey as shown in Fig. 1(a) (Multimedia view), thus indicating that the honey is more viscous in this scenario.

(ii) Viscosity with a small applied stress

1. Deposit the whipped cream and honey in separate small serving dishes.
2. Using the two metal spoons, simultaneously scoop a small volume (1–3 mL) of each material and hold the spoons above the dishes and rotate, so that the flatter side is vertical.
3. Observe that the honey immediately begins to drip off the spoon as shown in Fig. 1(b) (Multimedia view), while the whipped cream does not drip at all (alternatively, a small amount of whipped cream may fall of the spoon, but a static amount should adhere over long times). This indicates that the whipped cream is much more viscous in this scenario and also appears to adhere to the earlier presented definition of solids as materials which hold their own shape.

From the results of these experiments, it should be apparent to the audience that the answer to "which material is more viscous" is not straightforward in this comparison. Here, the presenter may designate the honey as a "simple" (or Newtonian) fluid, a material that has a viscosity that only depends on temperature, and which flows and takes the shape of its container no matter how one may push or pull on it. The whipped cream contrasts this and may be designated as an example of a "complex" (or non-Newtonian) fluid. At large applied stresses, the whipped cream behaves as a low viscosity fluid; at small applied stresses, whipped cream behaves as an apparent solid since it appears to hold its own shape and, thus, can be considered to have an extremely high resistance to flow. To answer the earlier posed question, the presenter should reiterate that whether whipped cream is more or less viscous than honey depends on how hard one pushes on the material, which is why it is considered an example of a complex material.

To conclude this demonstration, the presenter may speak more broadly about the field of rheology and explain how the study of

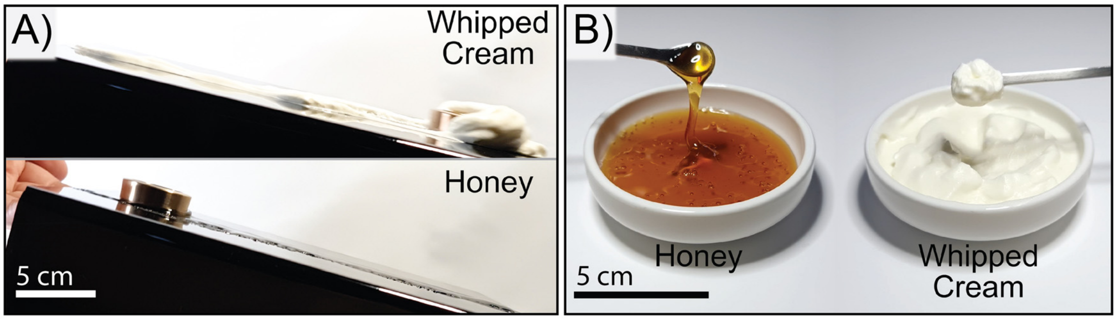

FIG. 1. Comparison of the behaviors of honey and whipped cream with large and small applied stresses. (a) A heavy weight slides much more easily on whipped cream than on honey due to the whipped cream being less viscous. (b) Honey readily drips off a spoon while whipped cream appears to be immobile due to it being more viscous. Multimedia views: https://doi.org/10.1063/5.0083887.1; https://doi.org/10.1063/5.0083887.2

complex materials is concerned with materials that have properties that are a function of some physical input. In the example of whipped cream, the property of viscosity depends on how much stress one applies to the material, but there are many different categories and types of complex materials that cannot be covered in a single demonstration. The wide variety of complex materials are often categorized by microstructure[1] or by rheological phenomena (e.g., the four key phenomena of rheology:[6] viscoelasticity, shear thinning, shear normal stresses, and extensional thickening). If desired, one may transition from the observed behavior of whipped cream to discussing other materials and applications that rely on similar rheological behavior; cake frosting and toothpaste are pedestrian examples that audiences may identify on their own when prompted, but the presenter may also take the opportunity to discuss cutting edge applications like direct-write 3D printing.[12,13]

Depending on the availability of resources, several variations of the first experiment may be performed. By reducing the angle that the surface is raised to or by using a smaller weight (between 1 and 10 g), one may also demonstrate the solid-like, low applied stress behavior of the whipped cream. Alternatively, one may simply shear the materials between one's fingers and rate the perceived viscosity. Based on the informal polling, audiences are very receptive to the idea that whipped cream is less viscous than honey, and so the presenter's testimony may be sufficient. However, the clear visual evidence of the sliding weights greatly strengthens the demonstration and should be performed if possible.

III. THE BIG PICTURE OF RHEOLOGY AND THE IMPACT OF PROCESSING

A useful organizational framework for understanding and teaching rheology is the so-called "big picture of rheology" shown in Fig. 2 that relates material microstructures to macroscale deformation and flow through rheological properties and measurements. This demonstration introduces the idea that changing a material's microstructure by applying different processing conditions has an impact on rheological properties as well as the macroscale behavior and performance. Here, the performance is understood broadly to mean the perceived texture and mouthfeel of the food material. The audience is expected to be comfortable with the idea of proteins in eggs that transform their configuration and form a gel network during the cooking process; this concept is commonly presented to broad audiences like at museums of science and technology.[14] This demonstration uses a preparation of cheesecake in a jar, the recipe for which is given in the Supplementary Information. For ease of reproducibility, it is recommended that two jars of cheesecake be prepared prior to beginning the presentation using a sous-vide method as shown in Fig. 3(a).

A. Materials

Two jars of cheesecake (see the supplementary material).
One stir rod or fork.
Two small serving dishes.
Two small spoons.
Optional: the white of one hard-boiled egg.

B. Procedure

As background information, the audience is reminded of the common explanation for the behavior of eggs during cooking. Namely, that proteins are present in the egg, and that they tend to unfold when heated and then linking with one another to form a

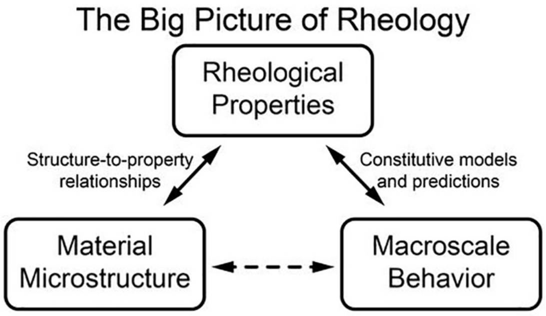

FIG. 2. The big picture of rheology depicts the relationships between material microstructure, rheological properties, and macroscale behavior and is a useful organizational framework in rheology education. Connecting the microstructure and macroscale behavior (dashed arrow) of different material systems can be considered an overall goal of the discipline of rheology, but rheological properties are often used to bridge this challenging gap using structure-to-property relationships and constitutive models and predictions.

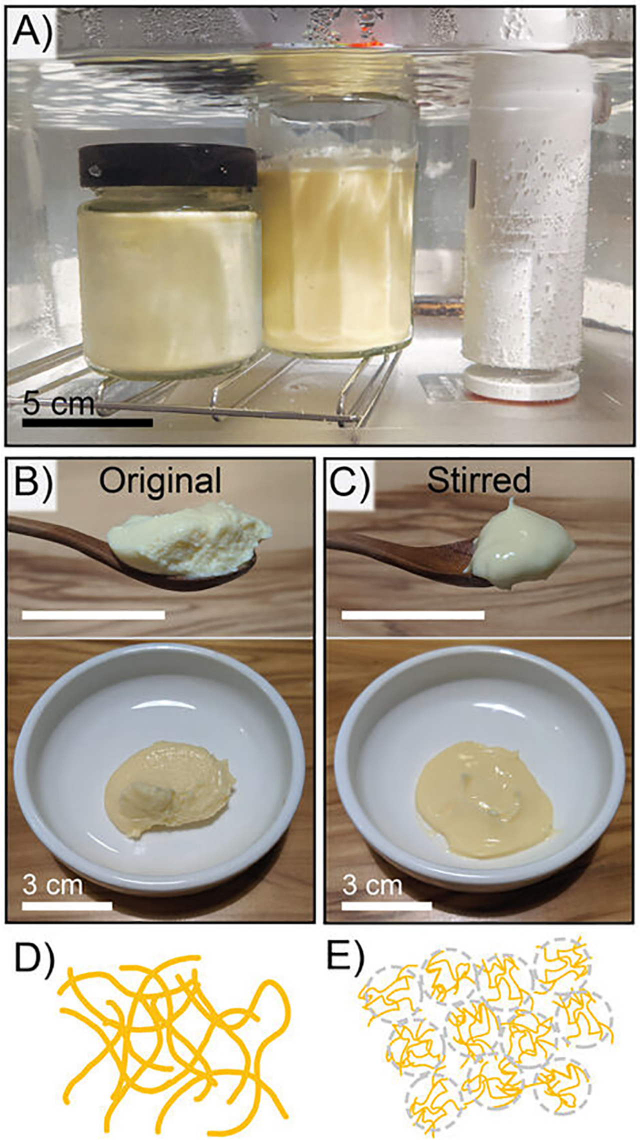

FIG. 3. (a) Recommended preparation method for jarred cheesecake (see the supplementary material for full recipe). Comparison of texture and flow behavior of (b) original vs (c) vigorously stirred cheesecake. Schematic representations of (d) a sample-spanning gel network and (e) a jammed microgel suspension microstructures. Microstructure schematics are adapted from Nelson *et al.*[8]

network. Thus, a cooked egg is an example of a solid material with a gel microstructure, a sample-spanning network of elements that interact via attractions.[15] Here, it may be worth the presenter noting that the colloquial usage of "gel" (e.g., with hair-gel) is not the same as the more modern technical term common in rheology and materials science.[16] Elaborating on the egg behavior, the presenter discusses how the gel network that composes a cooked egg does not go away after cooling, and also cannot reversibly break apart and heal. Optionally, the presenter may demonstrate this concept using a hard-boiled egg white, showing that it does not seem to exhibit any flow behavior and instead will brittlely break apart when pulled on and cannot re-heal spontaneously. The presenter then explains that due to their ability to form a gel, eggs are commonly used to provide structure and mechanical robustness in a variety of recipes, including cheesecakes.

The presenter then shows the two jars of cheesecake and scoops out a small amount from each jar using the spoons and shows them to the audience; both foods should appear roughly identical and as shown in Fig. 3(b) as they have the same ingredients and were prepared in the same way. It is encouraged to ask the audience to describe what they observe regarding the texture, shape of the material, and so on. The presenter should emphasize that the formation of a gel network from the eggs in the recipe helps result in a material that can hold its shape and has a noticeable stiffness. The presenter then deposits the material from both spoons into one of the serving dishes. In one of the jars, vigorously stir the cheesecake using a stir rod or fork for 1–2 min while attempting to entrain as little air as possible; check the material occasionally and stop when no lumps are apparent. Scoop out a small amount from the stirred jar and show the audience; the food should appear similar to Fig. 3(c). Deposit the stirred material in the second serving dish and ask the audience to describe the differences in appearance between the stirred sample and the two unstirred samples, which should be significant. The original cheesecake has a rough surface texture and will break in a somewhat brittle manner when pulled on, similar to what was discussed with the hard-boiled egg example. The stirred sample on the other hand will yield and flow smoothly and appears to re-heal when pressed together. The presenter may then eat the two samples and compare the mouthfeel for the audience; in the author's experience, audience members who later attempted these experiments on their own commonly described the stirred sample as softer and "creamier."

Since the two cheesecakes were prepared identically, one cannot attribute the final difference in behavior and texture to the ingredients (formulation) or cooking process, it must be solely due to the mechanical agitation that was performed in front of the audience. The presenter then explains that the difference in observed behaviors is due to a change in the microstructure, brought about by the mechanical processing. In the original cheesecake, one expects that a sample-spanning protein network forms due to the presence of the eggs, shown schematically in Fig. 3(d). On stirring, this network breaks apart into smaller domains that do not re-heal, as anticipated from the behavior of the hard-boiled egg. Thus, one would expect that the microstructure of the stirred cheesecake more closely resembles a jammed microgel suspension as shown schematically in Fig. 3(e). Concentrated microgel suspensions are a well-studied class of yield-stress fluid, materials that are capable of bearing a static load but yield and flow above a characteristic stress, i.e., a yield stress.[17] Unlike the sample-spanning network of the original cheesecake, which breaks and forms a rough texture, the microscopic packed microgels of the stirred cheesecake are more likely to slide past each other smoothly, explaining the difference in appearance and mouthfeel of the two materials. Many food materials and consumer products possess a yield stress.[18,19] As an optional exercise to promote the development of intuition for complex fluid properties, the presenter or audience members may attempt to determine the approximate yield stress of the stirred sample using Fig. 4, which depicts the nominal shear yield stresses of various food and consumer products.

To conclude this demonstration, the presenter should again speak more broadly about rheology and reiterate that the behavior of

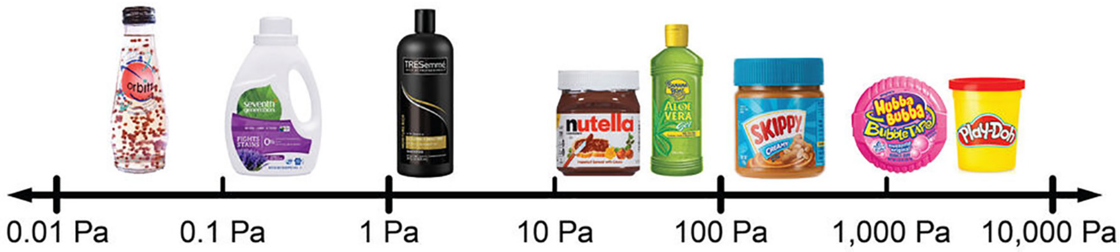

FIG. 4. Nominal shear yield stresses of various food and consumer products for context and development of intuition for yield-stress fluids. From left to right: Orbitz beverage,[20] laundry detergent,[21] shampoo,[19] Nutella,[22] aloe gel,[4] peanut butter,[23] bubblegum tape,[22] and Play-Doh.[24]

materials often does not depend only on their ingredients but also on their processing and microstructure. The big picture of rheology depicts how rheologists are often interested in how complex material properties depend on aspects of a material microstructure, and how these complex properties might then be used to predict the macroscale behavior of a material. Combining these relationships, a rheologist might also be interested in targeting a particular macroscale performance and designing a material with a microstructure that gives the necessary rheological properties to achieve that performance.[8]

To describe how the concept of microgel suspensions is widely applicable, the presenter may discuss how one of the household items that is most often considered a "gel," hair-gel, is actually a microgel suspension of the additive carbomer.[25] Furthermore, the act of shearing a gel network to break it into microgel domains is not merely a novel way to obtain a different food texture. In materials research, microgel suspensions are an emerging class of material for use in biotechnology and 3D printing, and fragmentation of a larger gel network is a simple and convenient way to obtain them.[26]

IV. OUTLOOK

This work provided a taste of the content produced over the past two years by The Soft Matter Kitchen. In 2021, the website received a total of 700 unique visitors and has been considered successful at contributing to increasing awareness of rheology globally. Of the over 1000 global visits in 2021, 52% were from the US, and 32% were from Singapore where the author is based. Ongoing efforts to promote engagement in Singapore and Southeast Asia include articles discussing the rheology of local cuisine, and the translation of select articles into Chinese by a local volunteer. Informally gathered feedback from visitors to the website as well as from audience members at several live presentations indicated that their understanding of rheologically complex materials was improved and cited the accessibility of the demonstrations. Going forward, The Soft Matter Kitchen will continue to develop new food-based content, with a planned focus on video components and further interaction with the larger rheology community.

SUPPLEMENTARY MATERIAL

See the supplementary material for the recommended preparation procedure for cheesecake.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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