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Do-It-Yourself Rheometry

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Abstract

We describe the structure and outcomes of a course project for do-it-yourself (DIY) rheometry. Although the project was created in response to the shelter-in-place orders of the COVID-19 pandemic, the student learning outcomes were so positive that we have continued implementing the project even when students have access to laboratory rheometers. Students select an interesting complex fluid, collect qualitative visual evidence of key rheological phenomena, and then produce their own readily-available flows that they quantitatively analyze to infer rheological properties such as yield stress, extensional viscosity, or shear viscosity. We provide an example rubric, present example student project outcomes, and discuss learning outcomes that are achieved with DIY measurements.

1. Introduction

Simple observations can provide a wealth of insight into rheological properties without (or before) having access to an accurate laboratory-grade rheometer. We have all probed rheology by stirring, spreading, kneading, poking, or otherwise interacting with the complex fluids in our own homes and especially in our kitchens[1,2]. Such observations provide qualitative evidence of non-Newtonian behavior, but they also can be quantitatively analyzed to infer rheological properties such as yield stress, extensional viscosity, or elastic modulus.

During the COVID-19 pandemic, we lost access to laboratory rotational rheometers that were foundational (or so we thought) to a course project to measure complex fluid properties. In response to the lack of lab access, one of the authors (RHE) reframed the course project as "shelter-in-place" rheology. Students were asked to select an interesting complex fluid, collect qualitative visual evidence of key rheological phenomena, and then produce their own readily-available flows that they quantitatively analyze to infer rheological properties. The four key phenomena of rheology[3] were used as an organizing framework of possible behaviors to probe (Fig. 1). This includes (1) shear thinning, (2) viscoelasticity, (3) shear normal stress differences, and (4) extensional thickening. Yield stress fluids and thixotropic behaviors are also mentioned in the prompts to students. These can be considered subsets of shear thinning[4] or separate phenomena, depending on the preferred pedagogy. For example, having a yield stress may be the most useful type of rheology for a complex fluid[8] and therefore deserving of being its own "phenomenon."

The at-home project grew into a broader realization that such visually compelling but imprecise tests can be incredibly useful, even when a rheometer is also available. The do-it-yourself (DIY) tests reveal many important aspects of measurement science: system-level thinking and assumptions, causes of violated assumptions, uncertainty propagation, and use of fluid mechanics analysis. Moreover, the highly visual demonstrations were useful to present alongside data collected on a rheometer: they provide additional evidence for the reported behavior and context for interpreting various rheological properties. The project was deemed so valuable that it has been implemented now twice as part of a graduate course on rheology at the University of Illinois Urbana-Champaign (remotely spring 2020 and in-person fall 2021) and once as part of a rheology short course (remotely summer 2020).

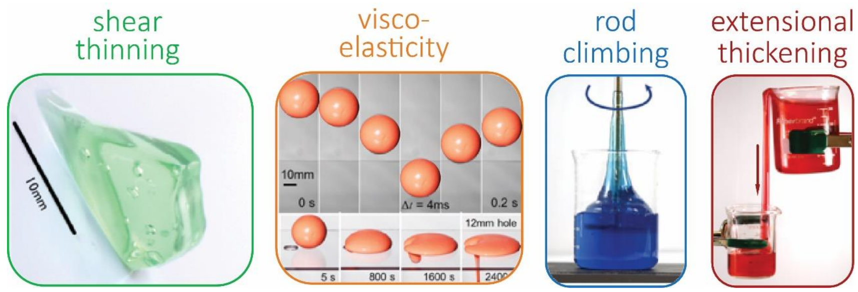

FIG. 1. The four key phenomena of rheology[3] serve as an organizing framework for the course project, e.g. as a checklist of possible behaviors to assess for any material of interest. From left: shear-thinning evidence of 1wt% Carbopol in water; viscoelasticity evidence with bouncing and flowing therapy putty; shear normal stress difference evidence from rod climbing of 2wt% PEO of $M_w \approx 8{\cdot}10^6$ in water; extensional thickening evidence via open siphon effect of 2.2wt% Polyacrylamide of $M_w \approx 5{\cdot}10^6$ in glycerol/water. (Figure adapted from Ewoldt & Saengow[4]. Reproduced with permission from Annu. Rev. Fluid Mech., 54, 413-441 (2022). Copyright 2022 Annual Reviews.)

Here we describe the educational structure of the project along with specific examples from student outcomes. Our objective is to inspire awareness of DIY rheometry in daily lives, demonstrate the value of DIY rheometry for teaching and research, and to provide a structure for using this project to teach measurement and data analysis as part of a course on rheology, fluid mechanics, or mechanics more broadly.

2. Course Structure and Student Examples

An example rubric for the course project is shown in Table 1. The final "Bonus" section can be used if there is access to accurate instrumentation to compare with the DIY measurements, but this is not required and was not used in the spring 2020 implementation.

We structure DIY rheometry into two main results sections: *qualitative* visual evidence followed by *quantitative* analysis to infer material properties. Qualitative visuals reveal the existence of certain rheological phenomena. Students were prompted to consider the four key phenomena of rheology[3,4] (Fig. 1) as a checklist of possible behavior of interest: shear thinning viscosity (and its relatives of shear thickening viscosity, yield-stress fluids, and thixotropy), viscoelasticity, shear normal stress difference, and extensional viscosity. Even with access to a rheometer, this is an important conceptual step to identify which phenomena may be relevant to a material of interest, and therefore motivates which quantitative tests to perform. For the DIY project, we allowed students to use different tests for the qualitative and quantitative analysis. For quantitative analysis, a single encyclopedic collection of test descriptions and working equations does not exist, although several practical tests have been described within textbooks[3,5].

Table 1. Course rubric that separately emphasizes qualitative evidence and quantitative inference.

Project description: The goal of this project is for students to measure the rheological properties of an interesting non-Newtonian fluid using easily-accessible flow scenarios. Your report/presentation should be organized as follows:
A. Introduction. Material description, material microstructure (to the extent known), and something interesting (cool photo?) that makes people want to keep reading/listening.
B. Results: Qualitative Visuals Qualitative demonstration of non-Newtonian properties. With photos and videos, prove that the fluid is not Newtonian. How many of the four key phenomena can you demonstrate (shear thinning, viscoelasticity, shear normal stress difference, extensional thickening)? What about yield stress, thixotropy, or other effects? (If you wish, the flow scenarios used here can be different than those in the following section. That is, you are not required to do quantitative analysis on all of the qualitative visuals here.)
C. Results: Quantitative Analysis Go forth and measure! Use quantitative analysis to interpret measurements of flow scenarios with your fluid. Measured properties should be relevant/interesting to how the material is used, or what can be observed in qualitative visuals. Consider shear versus extension. Linear versus nonlinear. Viscoelastic versus thixotropic. This will likely require two or more flow scenarios. Each flow scenario may feel like posing and solving a homework question but with flows you can create yourself. Each should include: a problem statement of the flow scenario, fluid mechanics modeling, constitutive model assumptions, and working equations relating measured observables to stress, strain rate, material functions, or constitutive model parameters. Simplify the mathematical modeling to be relevant but tractable. Aim for calculation of material functions whenever possible, but some flow scenarios will require assumptions of a specific constitutive model, for which you can fit model parameters. If that is the case, still try to make the inferred model parameters interpretable, e.g. by showing the material functions associated with the model fit parameters.
D. Discussion Discuss how the microstructure of the material may be responsible for the observed rheological behaviors. Discuss the limitations of each flow scenario (Pipkin space coverage? Measurement uncertainty? The need to assume a constitutive model *a priori*?), and possible ways to address these in the future.
E. Conclusions Give your perspective on the value of this project for integrating and applying course concepts.
F. Bonus Measure the rheological properties of your material using an accurate instrumented setup, such as a rotational rheometer, dynamic mechanical analyzer (DMA), filament stretching rheometer, or capillary-breakup extensional rheometer. Compare the results, experimental conditions, assumptions, and limitations of these more accurate instrumented measurements with your DIY rheometry measurements. Comment on the benefits of having do-it-yourself rheometry measurements before making more detailed measurements.

The resulting student projects have included a wide range of materials and a wider range of tests. Three specific examples are shown in Figure 2: buttercream frosting yield stress, toothpaste extensional viscosity, and yogurt shear thinning viscosity. These three case studies from spring 2020 (no access to rheometers) are described in some detail below to provide a sense of what DIY tests were performed and the level of analysis in the working equations. The following text excerpts from student reports describe the tests and analysis:

Student A: (Buttercream frosting)

> *The material will be placed between two parallel circular plates made of cardboard and put under compression loading. Three ramekins and water will be used to load the specimen. The loading will be increased gradually until the material yields, then the total loading that causes yielding was measured using a kitchen scale.*

Student B: (Toothpaste)

> *The toothpaste is squeezed from the tube slowly until it drips. Using slow-motion video and ImageJ, the position of the slug and center diameter are measured in time. The known frame rate of 240 fps [from a smartphone] and a coin being dropped are used to compare the toothpaste extension to gravity alone. Assuming a cone shape of the slug to estimate its mass, we can infer the total stress experienced by the toothpaste filament. And from the changing length, we can infer an approximate extension rate.*

Student C: (Yogurt)

> *A quantitative analysis was performed to determine the dependence of the apparent viscosity on the applied stress and resulting shear rate. The experiments were performed with stirred yogurt in the liquid state. The flow type is assumed to be simple shear, controlling the amplitude of the applied shear stress that is believed to be constant [in time] throughout the experiments. The angles tested were θ = 9°, 25°, 40°, and 52°.*

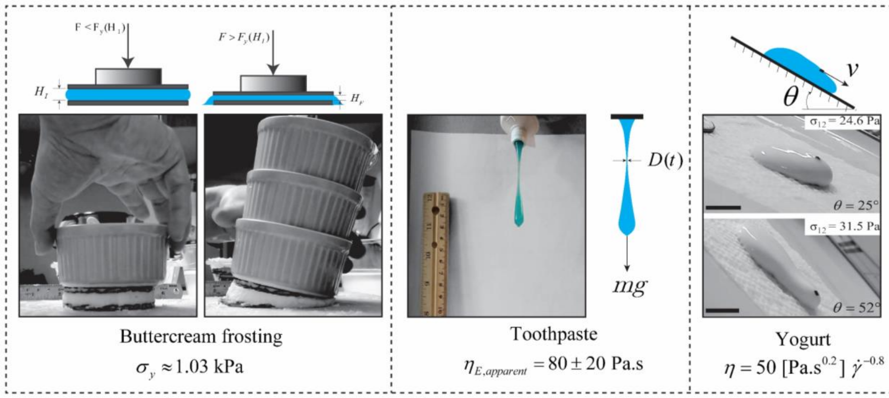

FIG. 2: Student examples from course projects (photos) paired with schematics representing the associated test. From left: measurement of the shear yield stress of buttercream frosting from compression test; extensional viscosity of toothpaste from gravity-driven filament stretching; shear viscosity from an inclined plane method with yogurt at different inclination angles fit to a non-Newtonian power-law model.

2.A Yield Stress Example: Compression Squeeze Flow Analysis

The compression test, also known as squeeze flow[6], is shown as a schematic in Fig. 2. A yield-stress fluid will not flow until a sufficient force is applied. Such an observation of a critical force F_y provides qualitative evidence of yield-stress fluid behavior and can be quantitatively analyzed. The resulting deformation field may be complex but at small gaps this will be dominated by shear deformation. For a yield-stress fluid, if one assumes the limit of perfectly plastic behavior (neglecting rate dependence of the shear stress), the analysis gives an analytical result to relate the applied compressive force to the shear yield stress[7]. The analysis proceeds by assuming the sample is contained between parallel circular plates of radius R and an initial gap H_I that is small $\left(H_I/R \ll 1\right)$, with a compressive force F imposed. The yield stress is indicated either by the critical force to create flow, F_y, or the gap at which flow stops, H_F, for a known applied force F. For a perfectly plastic yield stress fluid, the normal load F_y is related to the shear yield stress σ_y by considering a force balance (accounting for the radial pressure gradient)[7], giving

$$F_y = \frac{2}{3}\sigma_y \pi R^2 \left(\frac{R}{H}\right). \tag{1}$$

Rearranging eqn. (1) to infer σ_y yields

$$\sigma_y = \frac{3F_y}{2\pi R^2}\left(\frac{H}{R}\right). \tag{2}$$

The student followed this analysis to obtain the yield stress for buttercream frosting by applying weight to create the onset of flow (static yield stress), as shown in Fig. 2. The student observed onset of flow for an applied mass (measured afterward with a kitchen scale) of m = 943 g, and controlled initial geometry reported as R = 3.5 cm and H = 1.0 cm. Using this in eqn. (2) gives an estimate of shear yield stress σ_y = 1.03 kPa for the buttercream frosting. This seems reasonable, given that other thick pastes, such as peanut butter, have yield stress on the order of several hundreds of Pa[8,9]. However, we note that the student analysis did not include uncertainty of the calculated yield stress value, e.g. how uncertainty propagates with the experimentally measured variables in eqn. (2). This is an important concept in measurement science and can be implemented in the course project by pointing students to the general concept for uncertainty propagation, which for a given function of $y = f(x_1, x_2, .., x_n)$ is given by[10]

$$(\delta y)^2 = \sum_{i=1}^{n}\left(\frac{\partial f}{\partial x_i}\right)^2 (\delta x_i)^2 \tag{3}$$

for small deviations. Applying this to eqn. (2) for the yield stress estimate results in the expression $\delta\sigma_y = \sigma_y\sqrt{(\delta F_y/F_y)^2 + (\delta H/H)^2 + (3\delta R/R)^2}$, and assuming m = 943g ± 20g, H = 1cm ± 0.2 cm, and R = 0.35cm ± 0.2cm gives $\sigma_y = 1.03$ kPa ± 0.3 kPa resulting in a 26% uncertainty in the inferred yield stress. Furthermore, the small gap analysis above may not be obvious to a student, e.g. they may start instead with the simpler analysis of uniaxial compression yield stress, $\sigma_y = F_y/(\pi R^2)$. This will always give a larger estimate for σ_y than eqn. (2). For the student's results here, the over-estimate would give σ_y = 2.4 kPa.

Several other tests are available to quantitatively infer a shear yield stress[5], and many of these were used in student projects by their own choosing. Additional tests may include the inclined plane test, slump test, compression test, penetrometer, imperfect squeeze test (back extrusion), the consistometer flow test (gate-opening gravity current), and conduit flows. Interestingly, many of these DIY tests are gravity-driven, as with the other student examples described here.

2.B Extensional Viscosity Example: Gravity-Driven Filament Stretching

The toothpaste in Fig. 2 is squeezed from the tube slowly until it drips. This gravity-driven drip test could be used to qualitatively demonstrate extensional yield stress[11], and quantitatively infer it, but here the student was more ambitious and inferred an extensional viscosity from the rate of extension. The small diameter $D(t)$ was difficult to measure with a smartphone at a high frame rate (240 fps). Instead, the student used an approximate analysis based on the filament length based on observation of the tip position with time. The analysis is similar to a filament stretching extensional rheometer[12] but with significant approximations to estimate the strain rate, and with a loading history that is force-controlled with changing the diameter and therefore neither stress, nor strain rate, is held fixed during the experiment.

Considering these important system-level assumptions (just as we must consider them for actual extensional rheometry), progress can be made to estimate an apparent extensional viscosity. If we neglect acceleration effects, then tensile force is known and constant, and from a force balance the tensile stress is

$$T_{zz} = \sigma_{zz} - \sigma_{rr} = \frac{mg}{\frac{\pi}{4} D(t)^2} \tag{4}$$

where T_{zz} is the total stress, $\sigma_{zz} - \sigma_{rr}$ is the difference in the extra stress tensor components, $D(t)$ is the minimum diameter of the thread, and mg is the weight below the minimum diameter. The local extension rate is

$$\dot{\varepsilon} = \frac{1}{L}\frac{dL}{dt} = -2\frac{1}{D}\frac{dD}{dt}. \tag{5}$$

From these, the apparent extensional viscosity $\eta_{E,app}$ is defined as

$$\eta_{E,app} \equiv \frac{\sigma_{zz} - \sigma_{rr}}{\dot{\varepsilon}}. \tag{6}$$

The student used slow-motion video and ImageJ software to calculate the tip position as a function of time. The student assumed a cone shape to estimate the weight. Inertial acceleration effects were assessed experimentally in a clever way by observing the free fall of a coin and comparing this to the toothpaste extension. Analyzing the slow-motion video, the student noticed a significant difference in slopes early in the test, suggesting viscous resistance slowing down the toothpaste motion. As the filament stretches, the cross-sectional area drops quickly, reducing the viscous resistance until the acceleration effects dominate and the motion becomes gravitational free-fall. Because of this, there was a region of useful data only at short times where viscosity was significant. The student used this region to calculate an approximate extension rate of 5.4 s^{-1}. This, along with the estimated weight, was then used to calculate apparent extensional viscosity of $\eta_{E,app}$ = 80±20 Pa.s. This student included uncertainty in the analysis of their extensional viscosity estimate, demonstrating their understanding of some measurements science fundamentals. The student commented that the obtained value was within an order of magnitude of the extensional viscosities reported in the literature[13].

This simple experiment is similar to the famous experiments by Trouton[14] where the materials under examination were suspended from one end while to the other a weight was attached. More advanced analysis could be attempted. For example, the pendant drop extension analysis of Jones *et al.* monitored time dependent length, velocity, and acceleration to infer a time-dependent apparent extensional viscosity[15]; this would require more involved analysis of length versus time than the DIY experiment employed by the student. Stokes *et al.* analyzed the time-dependent extensional fall of a viscous fluid drop, including analysis of the break point time, although this was not framed as a way to infer viscosity[16]. An advanced DIY option is the constant force extension approach of Szabo *et al.* who considered an added mass m at the end of the filament to increase the forcing and access high extension rates at short times to probe viscoelastic effects[17]. This too requires more involved monitoring of length with time, and an assumption of a constitutive model whose parameters would be fit to the observations.

2.C Shear Thinning Viscosity Example: Inclined Plane Analysis

The yogurt on inclined plane example demonstrates how a function-valued property can also be estimated, here the shear viscosity $\eta(\dot{\gamma})$. The inclined plane test infers viscosity from the simple observable of the velocity at the top free surface, v_s. With precise instrumentation, this type of test has been used to measure the viscosity of dense suspensions up to 61% volume fraction, which could not be measured with rotational rheometers due to experimental challenges[18]. The method is visual and simple for do-it-yourself tests if one is comfortable with approximations.

In an inclined plane analysis, gravity induces shear stress that drives the deformation and flow, determined by the inclination angle θ with respect to the horizontal. The liquid thickness is h with a free surface on top. The tangential stress σ is a function of the y-location in the fluid where y is the distance above and normal to the inclined surface. Using the Cauchy momentum equation in the direction tangent to the surface (x-direction), neglecting acceleration and variation in x, the force balance is between gravity and shear stress, given as $-\rho g \sin\theta + \left(d\sigma/dy\right) = 0$. Assuming a shear-stress free boundary condition at the free surface $y = h$, integrating this equation gives the linear shear stress variation

$$\sigma = \rho g (h - y) \sin\theta . \quad (7)$$

Shear stress is zero at the free surface and maximum at the bottom. Therefore, the largest strains and strain rates are expected at the bottom. For a flowing Newtonian fluid, $\sigma = \eta\, dv/dy$. Substituting this into eqn. (7), integrating, and applying a no-slip boundary condition at the wall, the profile for the velocity v (parallel to the surface) is parabolic, given by[19]

$$v(y) = \frac{\rho g (2h - y) y}{2\eta} \sin\theta , \quad (8)$$

and setting $y = h$ gives the free surface velocity $v_s = \frac{1}{2}\rho g h^2 \sin\theta / \eta$. Using this to infer viscosity,

$$\eta = \frac{\rho g h^2 \sin\theta}{2 v_s} , \quad (9)$$

which shows an inverse relation between viscosity and velocity. The student used this Newtonian analysis to infer an apparent non-Newtonian shear viscosity, which is analogous to using Newtonian analysis with pressure-driven capillary viscometers to report an apparent shear rate, and analogous to using linear viscoelastic analysis with rotational parallel plate rheometry to report an apparent stress. Corrections are available for those flows; here the student used the approximate analysis.

Surface velocity was measured at four different inclination angles, and the student calculated the apparent viscosity from eqn. (8) for each angle. Viscosity was not constant, and this gives direct evidence for non-Newtonian behavior, even if the quantitative values are approximate. To report $\eta(\dot{\gamma})$, the student approximated the shear rate from the scaling relation $\dot{\gamma} \sim v_s/h$. Based on this, the student fit a power law model to obtain the relation $\eta = 50$ [Pa.s$^{0.2}$] $\dot{\gamma}^{-0.8}$, i.e. $m = 50$ Pa.s^n and $n = 0.2$. The power-law exponent gives strong evidence of non-Newtonian shear thinning behavior and shows that yogurt is dramatically shear thinning in this regime. The student concluded by assessing the credibility of measured m and n by comparing to reported values in the public literature for yogurt at low temperature, citing $m = 35.3$ Pa.s^n and $n = 0.232$ [20]. Fitting data to a model, in this case a simple power law model, enables the student to become familiar with data analysis (although the student did not comment on the goodness of fit). The student accounted for the uncertainty in the reported value of viscosity by applying eqn. (3) for uncertainty propagation to eqn. (9), resulting in the expression $\delta\eta/\eta=\sqrt{\left(2\delta(\Delta x)/\Delta x\right)^2+\left(\delta(\Delta t)/\Delta t\right)^2+\left(\delta(h)/h\right)^2}$. Assuming a 20% error in each of measured variables in eqn. (9) (velocity is measured by obtaining the distance traveled Δx with time Δt) the student reported that error propagates to 48% in the measurement of viscosity.

The analysis could be refined, even with the given data set, by considering the exact solution of a velocity profile for a power-law fluid. The actual shear rates will be larger than estimated from the simple scaling law. Since the stress is known from eqn. (6) which is applicable to both Newtonian and non-Newtonian flow, then the actual viscosity $\eta=\sigma/\dot{\gamma}$ will be *lower* than estimated above once a shear rate calculation is refined. For example, if we specifically assume the fluid to be a power-law fluid, the constitutive equation is $\sigma=m\left|\frac{\partial v}{\partial y}\right|^{n-1}\frac{\partial v}{\partial y}$ where n is the power-law index and the velocity profile is[21,22]

$$v(y)=\left(\frac{\rho g\sin\theta}{m}\right)^{1/n}h^{(1+n)/n}.\frac{n}{n+1}\left[1-\left(1-\frac{y}{h}\right)^{1+n/n}\right]. \tag{10}$$

The free surface velocity is then

$$v_s=\left(\frac{\rho g\sin\theta}{m}\right)^{1/n}h^{(1+n)/n}.\frac{n}{n+1}. \tag{11}$$

This is not an explicit equation for shear viscosity, but a means to indirectly infer constitutive model parameters m and n. The value of m and n can be obtained from eqn. (11) with a minimum of two inclination angles with associated free surface velocities. This process of considering approximate analysis, followed by more accurate analysis, is a useful framework for measurements with laboratory rheometers as well. Additionally, one could instead report the viscosity as a function of the more accurately known shear stress, $\eta(\sigma)$, or instead as shear stress versus shear rate $\sigma(\dot{\gamma})$. This touches on another general concept of measurement science where one can choose how to represent the data.

FIG. 3: Additional examples of DIY rheology. From left: peanut butter on a graham cracker with a toothpick for scale; chewing gum extension test using added weights (coins); egg whites tested with propagation of viscoelastic shear waves initiated by sudden rotational displacement of the bowl.

3. Discussion

The specific examples above capture some broader trends we have observed across the multiple implementations of DIY rheometry. Here we describe these other course project/activity embodiments and then discuss those broader trends.

The project structure was nearly identical in spring 2020 and fall 2021, but with the added bonus in fall 2021 of having access to laboratory rotational rheometers (see rubric part F.Bonus in Table 1). Selected example photos from fall 2021 are shown in Fig. 3 (chewing gum and egg whites).

The concept was also used in August 2020 in a simplified form during a week-long short course on rheology[23]. There, the focus was exclusively on yield-stress fluids and attendees had only 30 minutes to find a yield stress fluid in their home or office and perform a test that qualitatively but convincingly demonstrated that it was a yield stress fluid. Quantitative inference of yield stress was posed as a stretch goal. Attendees presented results in small groups of three or four people while instructors moved between groups to act as consultants and respond to questions. Figure 3 shows an example used by a course instructor which demonstrates yield stress fluid evidence with peanut butter and uses a toothpick for a scale bar. The course activity focused on yield-stress fluids only, and a lecture described key tests and working equations as examples beforehand. This preparation seemed to enable attendees to make significant progress during the short 30-minute exercise, including some making quantitative estimates of yield stress.

In the course projects, students were free to choose any material of interest and had multiple weeks to complete the project. We noticed that most students choose materials with a yield-stress, unless specifically prompted otherwise. Examples include buttercream frosting, peanut butter, mayonnaise, egg white meringue, cookie dough, sesame paste, chewing gum, toothpaste, some yogurts, ketchup, tomato sauce, and tomato paste. This tendency to choose a yield-stress fluid maybe because they are very common in our everyday experience. Having a yield stress is one of the most useful types of rheological complexity[8]. Counter examples without a clear yield stress included silly putty, egg whites, salad dressing, and some yogurts. Sauces, shampoos, and liquid soaps are other readily-available examples without a yield stress. Knowing this tendency toward yield-stress fluids, one may choose to focus exclusively on them (as we did in the short course exercise), or the opposite and force a broad distribution of materials. The instructor could choose a selection of materials covering a known range of behavior or leave the students to identify a material of interest to them.

Whatever the chosen material, the four key phenomena served as a useful framework, and many students looked for evidence of all the key phenomena listed in Fig. 1, even for yield-stress fluids. For example, we believe this helped prompt the toothpaste project in Fig. 2 to consider extensional viscosity. That student also considered elastic modulus and thixotropy. The yogurt and buttercream projects of Fig. 2 also measured shear elastic modulus from inclined plane tests. With other projects, normal stress differences were checked with creative rod climbing tests at home (using toothpicks or chopsticks rotated by hand) and die swell tests (e.g. using syringes – although not commonly available in the kitchen, they are easily procured). We were delighted by some of the student creativity. For example, a project with egg whites placed many of them in a bowl and then used viscoelastic shear wave propagation to infer an elastic shear modulus.

We observed that most tests are driven by gravity and thus a known state of *stress* characterizes the flow for purposes of non-Newtonian behavior. For example, students used methods like measuring viscosity from inclined plane, yield stress from inclined plane[5], yield stress from force-controlled squeeze flow[7], yield stress analysis from slump tests[24–26], shear modulus from inclined plane, pressure-driven die swell analysis[4], gravity-driven extensional flow analysis[12], and many more. We noticed that students chose tests that were either given as examples during lectures or were specifically suggested by the instructor during consulting. Thus, students were not aware of many other possibilities for do-it-yourself rheometry tests. It would therefore be very helpful to have an organized collection of practical do-it-yourself tests for students to select from, preferably organized in terms of the key phenomena of rheology, rather than the type of flow or type of material. We are currently working on such a review of methods which we believe will be useful not only for coursework and instruction but also for research and technical communication.

Implementation of the project supported several learning outcomes. Students engaged with measurement science concepts deeply, since more imagination and thought were required compared to projects involving long-established scientific instruments. The project helped the students to understand how to measure rheological material functions from a simple setup experimentally. Even if students have access to a rheometer, performing DIY rheometry helped the students to understand the importance of sample consistency, and to analyze system level errors, inertia effects, and non-ideal errors including slip. For example, some students used tissue paper to create a roughened bottom surface for inclined plane tests to calculate the yield stress, giving students a better hands-on experience of this non-ideal error. Many students also calculated uncertainty from their measurements, understanding system level errors and how this propagates to calculating a rheological property of interest.

4. Conclusions

We initially called the project shelter-in-place rheometry due to the acute nature of the COVID-19 pandemic and shelter-in-place rules during the spring 2020 semester. But we realized that the idea is more general and have since taken to calling it do-it-yourself (DIY) rheometry. We have found DIY rheometry to be useful in teaching and training students in the areas of rheology, fluid mechanics, and measurement. DIY evidence is persuasive, convincing, and understandable, and it complements more accurate laboratory measurements. It strengthens student understanding of measurement science principles and can be used whether or not a scientific instrument is available to make a rheological measurement.

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Data Availability Statement

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

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