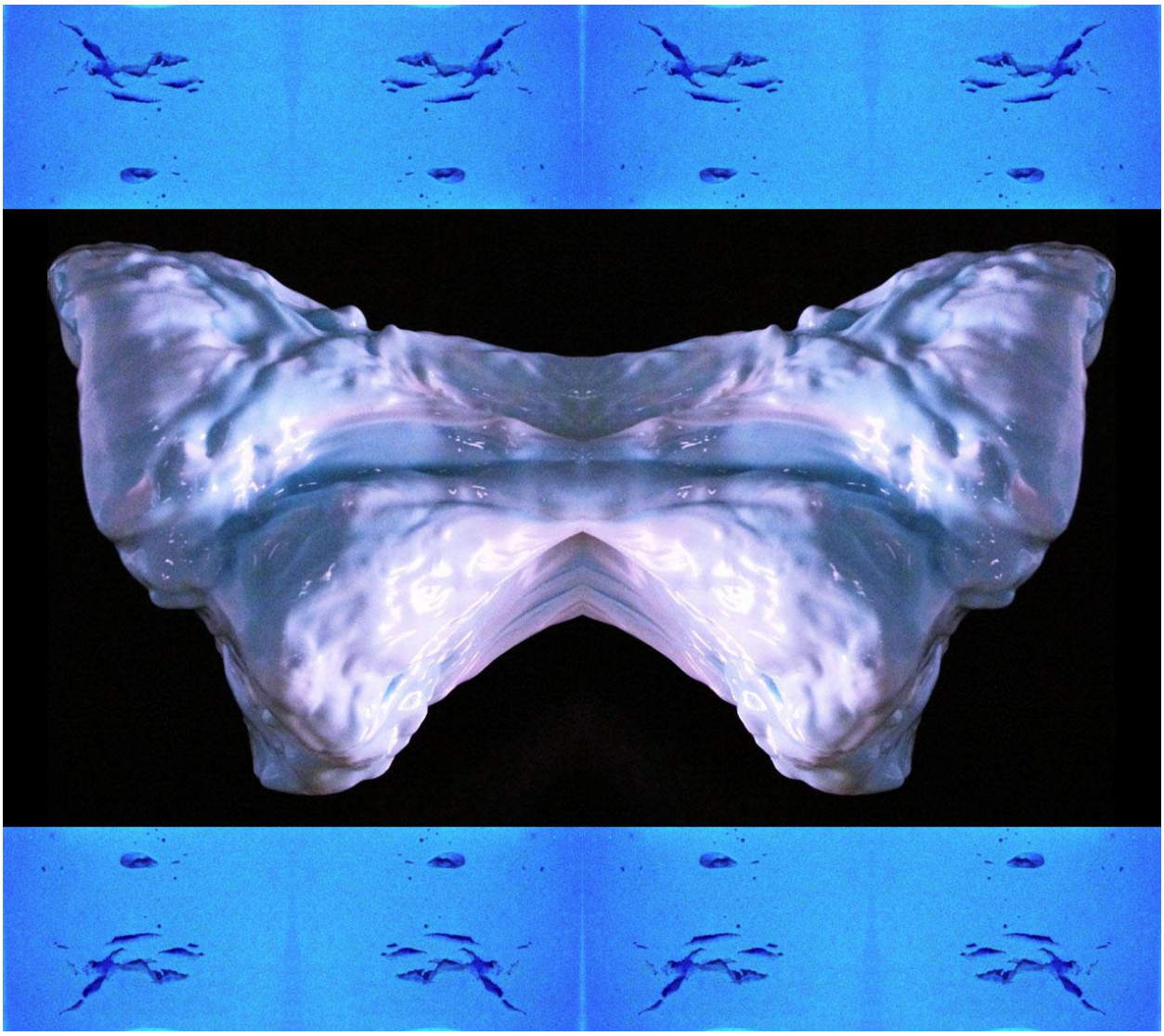
MIND WARP

An Artistic View of the Line between Fluids and Solids

Project 6: Group 3



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MCEN 4151: Flow Visualization

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Origins and Motivation

Mind Warp is the result of the sixth project, Group Project number 3, for the Flow Visualization class at the University of Colorado at Boulder. I wanted to explore those fluids which could behave like solids in an attempt to explore the line between a fluid and a solid. I set out trying to illustrate a fluid behaving like a solid and a solid behaving like a fluid. The first was fairly straight forward since shear-thickening fluids can achieve solid state properties at high shear rates and Oobleck is one of these fluids and is easy to make. Finding a viscoelastic polymer that is technically a solid but behaves like a fluid which is easy and cheap to make and easy to control for photographing was not as easy. The viscoelastic polymer used was technically a fluid state polymer which behaved in a similar manner as a viscoelastic solid state polymer but was easily controllable. The desire with these materials was to capture the polymer's flow and the Oobleck's fracture patterns. This was done using dyes, clear containers for side views, and much patience.

Special thanks to Beth Luke and Tyler Huck for assistance in set up, polymer and Oobleck manipulation, execution of the experiments, and clean up.

Experimental Setup

The experiment was setup in the Durning Lab in the Engineering Center at the University of Colorado due to adequate lighting control, available sinks, and space. A bowl was first filled with 3 pounds of cornstarch, adequate water to create a stiff Oobleck (about 4 cups), and neon green food dye. A second bowl was used to create the viscoelastic polymer called Slime. The slime is made by polymerizing the polyvinyl-alcohol, PVA, in Elmer's Glue All glue with the sodium-tetraborate in Borax. This was done by first mixing 24oz of glue with 24oz of warm water and electric blue food dye for visual effects. A mixture of 16oz water and about 2 tablespoons of Borax (more than enough to polymerize all of the PVA) was then prepared and mixed slowly into the blue glue water. The resulting polymer strings were collected, pressed together (over several minutes), and then allowed to flow into a near cylindrical disc and settle over about an hour. The Oobleck was transferred to a clear square container to allow side images as it was repeatedly stabbed with a large two pronged steal fork. The slime was then manipulated into a semi-ellipsoid and gripped (with several readjusted grips) and allowed to flow over the course of several minutes under its own weight.

Physics of Flow and Fracture

What All Qualifies as Viscous Material?

There are a vast number of materials which qualify as viscous materials and can be functionally modeled using equations with viscous terms. The most well-known of these are Newtonian fluids, but these only begin to scratch the surface of viscous materials. In general there are two major categories of viscous fluids: purely viscous materials, of which Newtonian fluids are included, and semi-viscous materials, also called visco-plastic materials. Figure 1 further breaks these down by minor categories and then into sub-categories (and types for Non-Newtonian fluids).

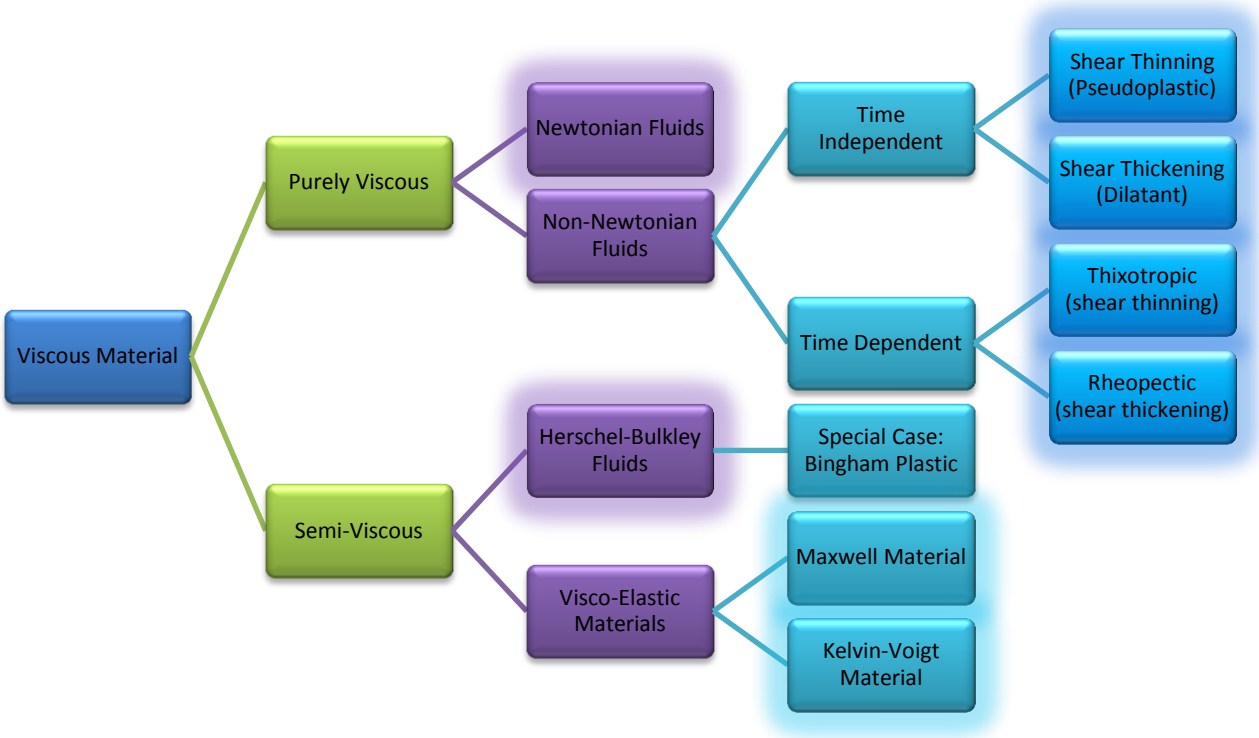


Figure 1: Break down chart for Viscous Materials. Note that all general end categories are highlighted.

Purely Viscous Materials

Purely viscous materials are those that can be described at any given temperature, pressure, shear rate, and time by a direct proportionality between the experienced shear stress and the resulting strain rate, or velocity gradient. In other words, there is no material property required besides those associated with viscosity directly. Those materials with time independent viscous properties can be modeled as a generalized Newtonian fluid where, at any given stress rate, Equation 1 holds where τ is shear stress, $\left(\frac{du}{dy}\right)$ is strain rate, and μ_{eff} is the effective viscosity. Newtonian fluids are essentially a special case of this model where the effective viscosity is a constant for all shear rates and μ_{eff} can be considered simply μ as in Equation 2 [Muanmai].

$$\tau = \mu_{eff}\left(\frac{du}{dy}\right)$$

Equation 1

$$\tau = \mu\left(\frac{du}{dy}\right)$$

Equation 2

Non-Newtonian fluids include the time independent fluids which can be fitted to the generalized Newtonian fluid model as well as time dependent fluids which cannot. In both cases, there are primarily two response types resulting from the appropriate stress application. These are the shear thinning response and the shear thickening response. For time independent non-Newtonian fluids, shear thinning fluids are called pseudoplastic and shear thickening fluids are called dilatant. Pseudoplastic fluids have effective viscosities that decrease with increasing shear rate, and dilatant fluids have effective viscosities that increase with increasing shear rate. Figure 2 shows the responses of dilatant and pseudoplastic fluids in comparison to Newtonian fluids with respect to shear rate [Muanmai].

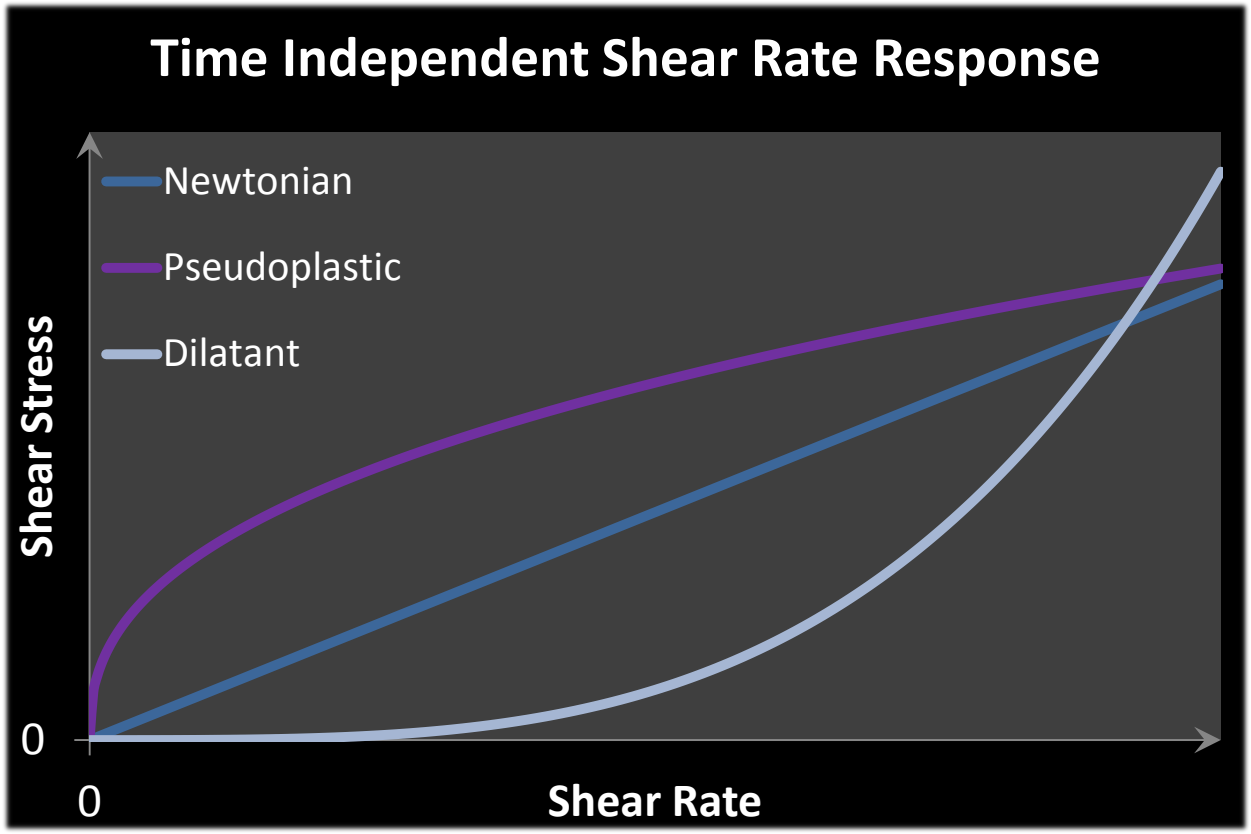


Figure 2: Shear stress as a function of shear rate for Newtonian, pseudoplastic, and dilatant fluids.

There are several models for the behavior of time independent non-Newtonian fluids with varying degrees of accuracy for different materials and ranges of shear rates. Some of these include the Cross model, Carreau model, and power-law model for non-Newtonian fluids. The simplest of these, which is used probably most often, is the power-law model which is demonstrated in Equation 3 below where K is the consistency index and n is the power-law index. Note that if n = 1 the fluid is a Newtonian fluid, if n < 1 the fluid is pseudoplastic, and if n > 1 the fluid is dilatant [Muanmai].

$$\tau = K\left(\frac{du}{dy}\right)^n$$

Equation 3

Time dependent non-Newtonian fluids can be modeled by several different and fairly complex models, but in general can be described as either thixotropic (shear thinning) or rheopectic (shear thickening). Thixotropic fluids are those with apparent viscosities that decrease with sustained application of shear stress. Examples of thixotropic fluids include paints, yogurt, and certain clays. Rheopectic fluids are those with apparent viscosities that increase with sustained application of shear stress. Examples of rheopectic fluids are gypsum suspensions and whipping cream. Figure 3 shows the relationship between these two fluid types and Newtonian fluids [Non-Newtonian Fluids].

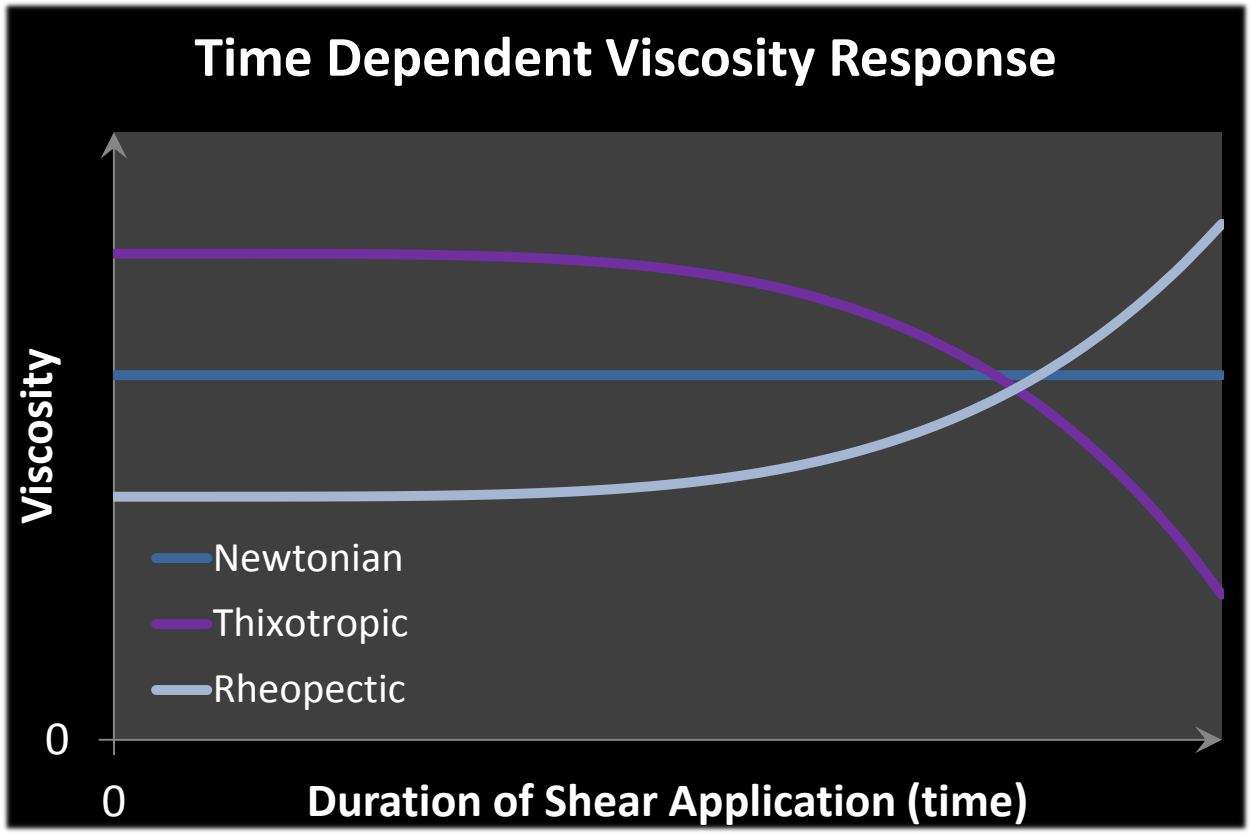


Figure 3: Viscosity as a function of time under an applied shear stress (load) for Newtonian, thixotropic, and rheopectic fluids.

Semi-Viscous Materials

Semi- viscous materials are those whose behavior cannot be described solely by an apparent or effective viscosity. These include Herschel-Bulkley fluids, which only exhibit a viscous behavior above a designated yield stress, and visco-elastic materials, which exhibit elastic properties in tandem with viscous properties. The Herschel-Berkley model can be considered a more general form of the power-law model for non-Newtonian fluids, however only those fluids which have a shear yield stress greater than zero are considered Herschel-Bulkley fluids. Equation 4 shows the Herschel-Bulkley model, where τ_0 represents the shear yield stress. Table 1 lists special cases of this model [Muanmai].

$$\tau = K\left(\frac{du}{dy}\right)^{n} + \tau_0$$

Equation 4

Table 1: Special Cases of the Herschel-Bulkley model. Note that Bringham Plastics are a special case of the Herschel-Bulkley fluids category [Muanmai].

Fluid	*K*	*n*	τ_0	*Examples*
Herschel-Bulkley	> 0	$0 < n < \infty$	> 0	Minced fish past, Raisin paste
Newtonian	> 0	1	0	Water, Juice, Milk, Vegetable Oil
Pseudoplastic	> 0	$0 < n < 1$	0	Applesauce, Orange juice concentrate
Dilatant	> 0	$1 < n < \infty$	0	Cornstarch solution, Custard
Bringham Plastic	> 0	1	> 0	Toothpaste, Tomato paste

Visco-elastic materials can be modeled using schematics composed of ideal elastic springs and ideal viscous dampers. The most simple of these models are comprised of a single spring and a single damper in either series or parallel. The series configuration (Figure 4A) describes the simplest model of a Maxwell material which initially deforms elastically and then continues to deform viscously under an applied stress. This means that Maxwell materials cannot return to their original state when a stress is removed, and for this reason Maxwell materials (despite being often called Maxwell solids) are technically fluids. Equation 5 shows the form of governing equations for these fluids, where σ is applied stress, ϵ is strain, E is the elastic modulus, μ is the viscosity, and dots denote time derivatives [Maxwell].

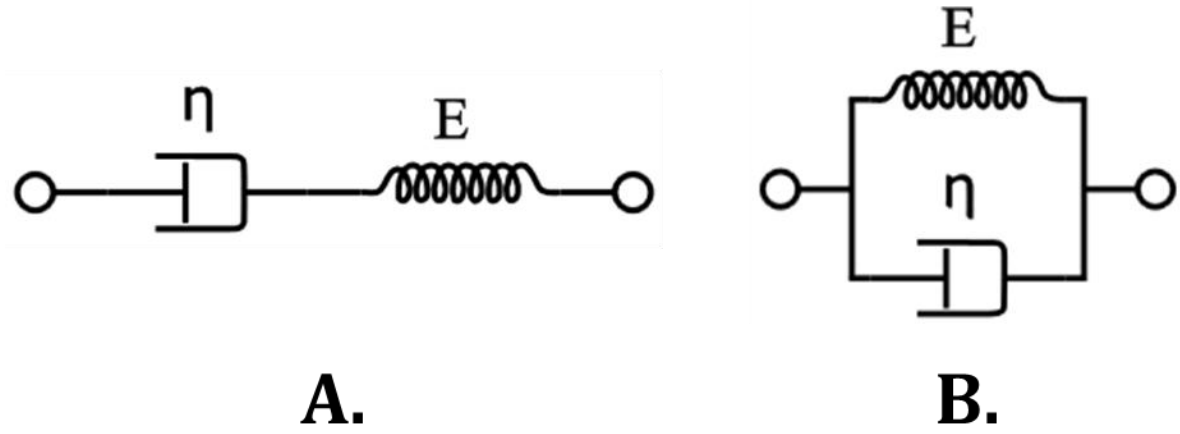


Figure 4: Spring and damper models for A. Maxwell materials, and B. Kelvin-Voigt materials

$$\dot{\epsilon} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\mu}$$

Equation 5

The parallel configuration (Figure 4B) describes the simplest model of a Kelvin-Voigt material which deforms slowly in a semi-viscous manner and exponentially decays toward a limit of elastic deformation. This means that when a stress is removed form a Kelvin-Voigt material it will eventually return to its original state. For this reason, Kelvin-Voigt materials (despite occasionally being grouped or discussed with non-Newtonian fluids) are technically solids. Equation 6 demonstrates the form of governing equations for these solids [Kelvin].

$$\sigma = E \cdot \epsilon + \mu \cdot \dot{\epsilon}$$

Equation 6

Walking the Line between Fluid and Solid

The single distinguishing factor between a solid and a fluid is whether or not the material can return to its original shape upon release from an applied stress field [Fluid (physics)]. This means that the molecular structure has to have a net elastic deformation upon application of a stress so that the molecules can pull (or push) their way back to their original position and alignment. With this in mind, it becomes possible for a liquid to temporarily become a solid without a formal state change, but not the other way around unless plastic deformation is considered. This means that although a viscoelastic solid may behave at a macroscopic level like a fluid, the molecular structure is only stretching or compressing and will therefore be unable to truly flow within the elastic regime. Should stress exceed the elastic limit of a solid, then the molecular shift, which could constitute flow in a viscoelastic material, corresponding to plastic deformation becomes a kind of one way flow without the ability to be undone by simply removing the applied stress field.

With that in mind, the formal distinction becomes less clear and convention is necessary to a certain extent. For example a Bringham plastic, conventionally considered a fluid, exhibits behave similar to a solid in that it yields at a specific elastic limit and begins to deform at a molecular level such that the original molecular structure is not guaranteed upon release of the stress. This behavior can be viewed as either a form of plastic deformation or of viscous flow (which can describe certain plastic deformations such as creep) and based on convention is categorized as the second. Kelvin-Voigt materials walk the other side of this line, where beyond a certain elastic limit they begin to deform permanently such that the molecular structure is not retained. By convention, the specific behavior of this deformation is deemed plastic and Kelvin-Voigt materials therefore solids.

The aim of the image was to walk this line as closely as possible. To this end, the Oobleck was stressed in such a manner as to force it into a temporary solid state. This allowed for fracturing to occur and a visual representation of a fluid behaving like a solid to be captured. The physics behind the temporary solid state reaction of a dilatant fluid is fairly complex and still debatable with respect to

certain technicalities. The general physics however has been well described by Waitukaitis and Jaeger in their paper on impact-activated solidification. Their experiments explored impact on the surface of Oobleck with various shear rates while monitoring the material density with x-ray imaging [Waitukaitis]. Figure 5 shows one of these impact tests and marks the resulting depression in the surface.

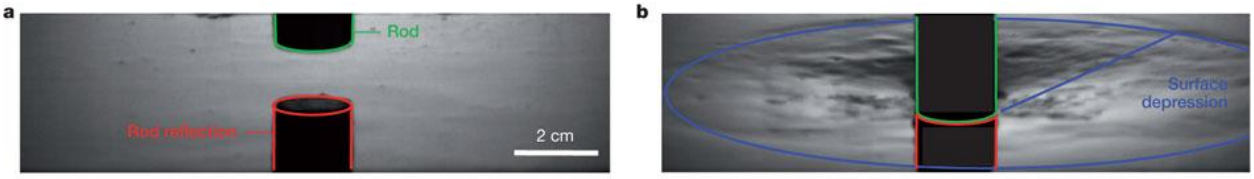


Figure 5: Example impact from experiments performed by Waitukaitis and Jaeger. a: before impact with length scale marked. b: after impact, at maximum Oobleck deflection. [Waitukaitis]

Essentially the suspended particles compress against one another in the direction of the applied stress forming a cone of temporary solid material expanding from the point of impact or applied stress. This is shown in Figure 6. An affected region of surrounding material fills an inverted conical shape from the base of the solid cone back to the surface; this is the region that makes up the conical depression around the impact region on the surface. Figure 7 illustrates the temporarily solidified and affected regions [Waitukaitis].

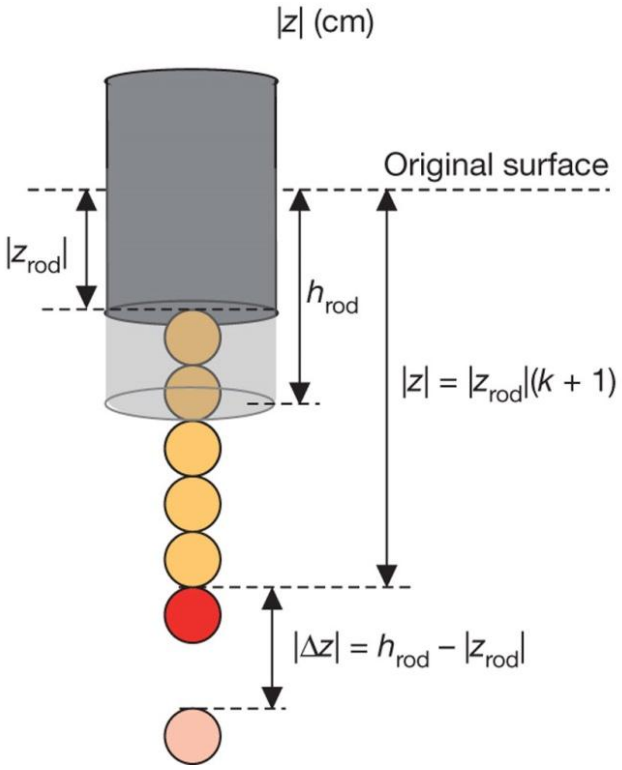


Figure 6: Compression process in an impacted shear thickening suspension where the rod first compresses suspended particles together and then translates them, compacting those below. [Waitukaitis]

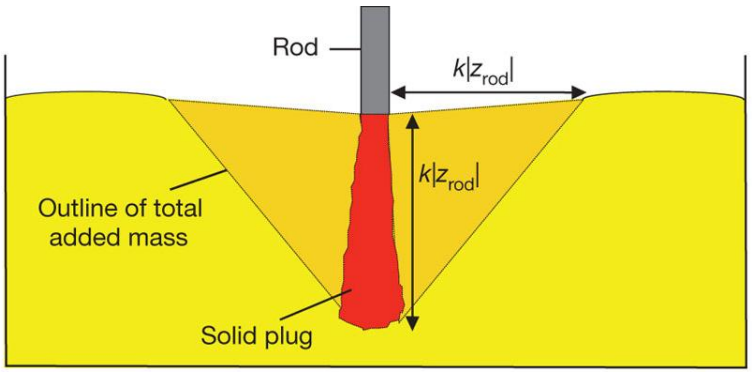


Figure 7: Schematic of the temporarily solidified region (solid plug) and the affected (added mass) region resulting from the impact of the illustrated rod. [Waitukaitis]

It is this phenomenon which allows for the propagation of fractures through Oobleck under certain conditions. For this image, the Oobleck was viewed from the side through a clear wall and impacted just inside the wall allowing a side view of this solid cone feature. The impacting instrument was a two pronged steal fork which could be driven into the solid region and allow for horizontal propagation of temporarily solid material along the wall's surface while cracking the two original solid plugs. This provided initial sites for crack's to begin propagating and material in the propagation direction solid enough to exhibit fracture characteristics. Figure 8 illustrates this theoretical behavior and marks a theoretically unstable surface at the intersection of the two growing primary solid regions. Note that if a crack were to propagate through this plane it would likely grow dramatically in size very quickly, feeding off of the instability.

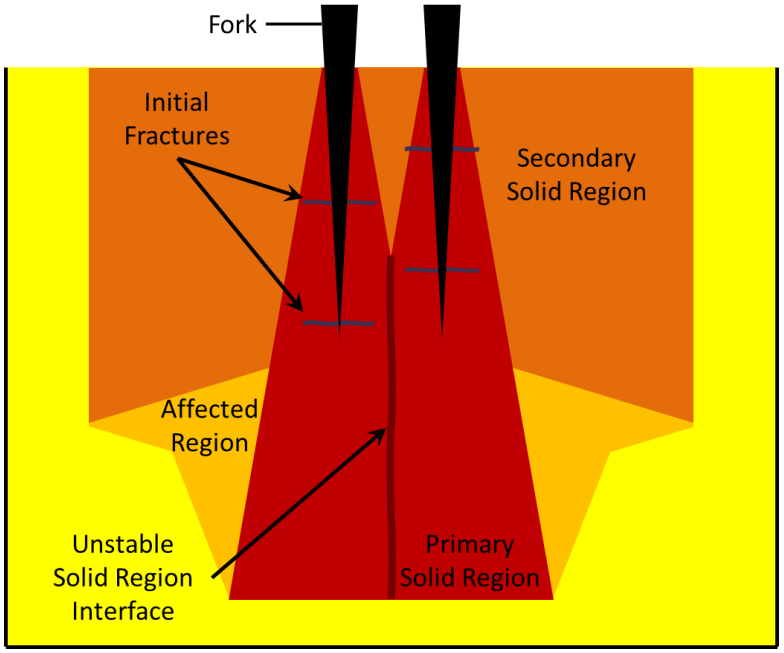
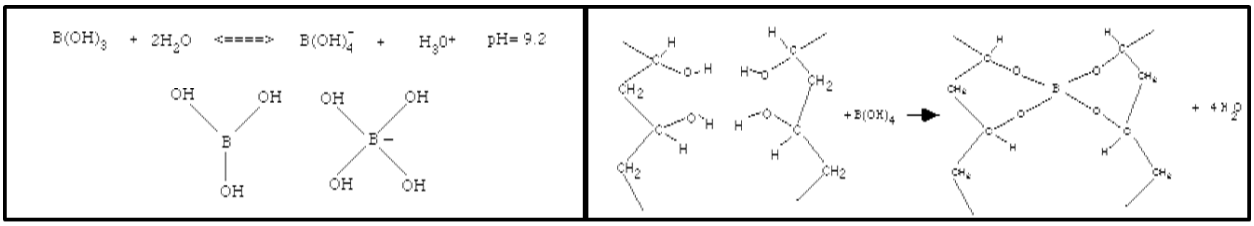


Figure 8: Schematic of theoretical solidification behavior of impact by two pronged fork.

Adding to the counter-intuitive behavior of the fracturing Oobleck was the flowing polymer mirrored in the center of the image. Although this was not quite a solid flowing like a fluid, the viscoelastic behavior of the Maxwell material made for adequate contrast to the temporary solid state behavior of the Oobleck. The Slime is produced by mixing dissolved PVA and dissolved sodium tetraborate. Once dissolved in water, the boric acid in the borate solution accepts hydroxide from nearby water molecules. This is schematized in Figure 9A. The now hydrolyzed boric acid can react with the PVA solution to cross link the PVA. This is schematized in Figure 9B. The byproduct of this process is copious amounts of water which is trapped within the cross-linked sections of the new polymeric compound. The resulting material has properties of both the polymer and trapped water and behaves according to the Maxwell visco-elastic model, technically defining it as a fluid [8.4.5].



A. **B.**

Figure 9: Slime formation process. A: Hydrolyzation of boric acid. B: Cross linking of PVA [8.4.5].

Flow Visualization Techniques

Both experiments were run with black cotton fabric draped behind to minimize light reflection and create a solid, high contrast background should the background be visible. The room was well lit and both experiments were performed directly under overhead lighting to maximize visibility and allow for both shadows and highlights. The Oobleck was fractured near the side of a clear flat sided container to allow for maximum visibility and minimum container influence on the photograph. The Oobleck was also dyed with neon green dye to maximize visibility and contrast. The container was stabilized from behind to prevent vibration and undesired motion. The slime was partially dyed only in order to help mark flow paths in the material. The slime was held from above with minimal grip to keep from blocking as much light as possible. The slime was allowed to flow for long enough to get distinctive patterns and flow characteristics.

Photographic Techniques

The camera used for both photographs was a Canon Power Shot SX 500 IS. For the Oobleck photograph, a high shutter speed was necessary to capture the fracture pattern before the temporary solidification ended. For this reason, a shutter speed of $^{1}/_{125}$ sec was used. Since more light was necessary, the highest possible f-stop at the given zoom was used (f/5.0). The ISO was also fairly high (800), as high as necessary to lighten the image to the desired degree. The camera was between 3 and 4 inches from the surface of the container to fill the photo as much as possible with the Oobleck. In

Photoshop, the image was cropped down to focus solely on the fracture patterns and overall contrast was increased with an overall curve. The red was reduced and the blues were accentuated using RGB specific curves. The greens were used to increase contrast even more to heighten the shadows. Figure 10 shows these curve adjustments for the Oobleck portion of the final image.

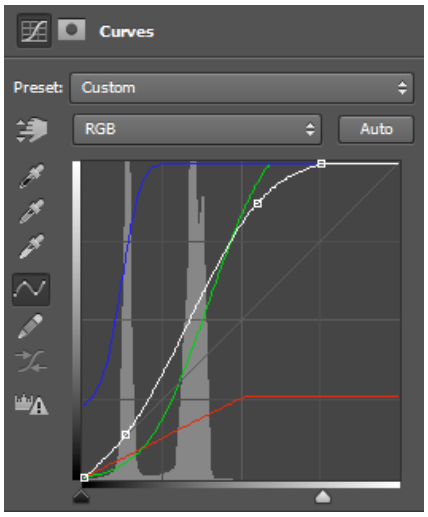


Figure 10: Curves adjusted to produce final Oobleck image.

For the slime photograph, the same settings were maintained because surprisingly, the resulting photographs had extremely high contrast and almost super realistic detail. The camera was used within 16 inches of the slime in order to fill as much of the photo as possible while keeping the image super clear. A list of all pertinent photo information for both images can be found in the appendix. In Photoshop, an overall S-curve was used to increase the contrast and remove mild background inconsistencies and the blues were also brought out more using RGB curves. Figure 11 shows these curve adjustments for the slime portion of the final image.

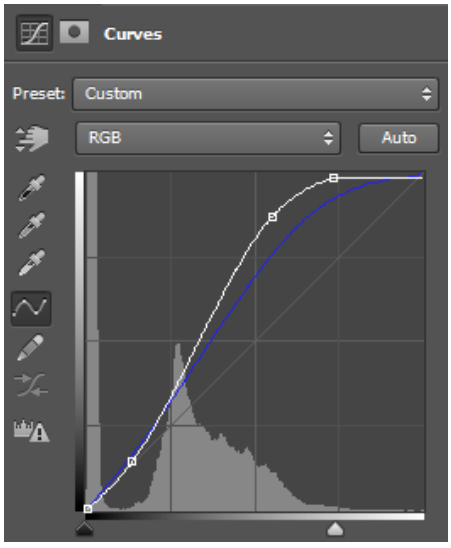


Figure 11: Curves adjusted to produce final slime image.

Discussion

To me this image provokes the curiosity that I wanted to inspire. The mystery and mind warping description of which is the more simple fluid and which has elastic properties adds to the complex curiosity inspired by the image. The color adjustments work well together to create a balanced image in color and the replication helps balance in context. My only issue with the image overall is the noise that is present (especially in the Oobleck) as a result of the high ISO. The physics displayed is well captured and shows a nice counter-intuitive contrast. A compilation of more viscous categories and types would have been even more interesting, though much more involved. Future developments could include a wider spectrum of these viscous materials, or interactions between them, however the later would require video to truly capture the interactions well.

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Appendix

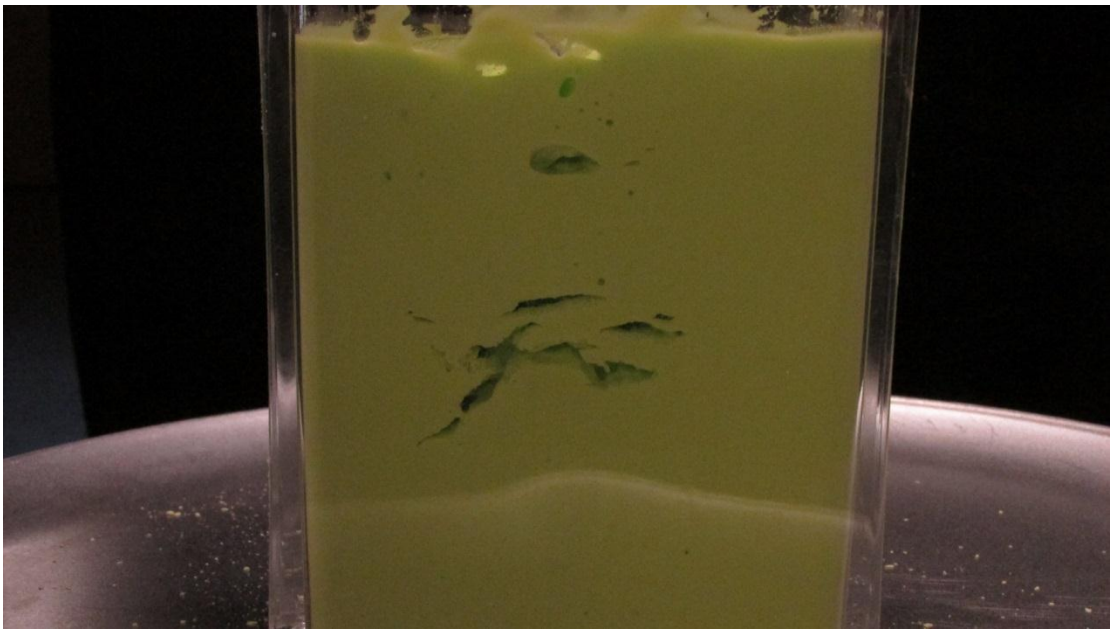
Photographic Information {Oobleck Photo}

Photograph Date and Time	**20 April, 2013 at 14:05**
Camera Type	**Canon PowerShot SX500 IS**
Shutter Speed	**1/125sec**
Aperture	**f/5.0**
ISO Setting	**800**
Lens Focal Length	**16.7 mm**
Distance from Lens to Impact	**16 inches**
Field of View	**Approximately: 25 x 45 cm**
Original Image Size	**4608 x 2592 pixels**
Final Image Size	**2592 x 4608 pixels**

Photographic Information {Slime Photo}

Photograph Date and Time	**20 April, 2013 at 13:54**
Camera Type	**Canon PowerShot SX500 IS**
Shutter Speed	**1/125sec**
Aperture	**f/5.0**
ISO Setting	**800**
Lens Focal Length	**10.1 mm**
Distance from Lens to Impact	**4 inches**
Field of View	**Approximately: 12 x 22 cm**
Original Image Size	**4608 x 2592 pixels**
Final Image Size	**2220 x 1569 pixels**

Original Oobleck Image



Original Slime Image