Flow Visualization of Dripping Oobleck

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Introduction

Figure 1: Dyed Oobleck Dripping to Form "Stalactites"

As an experimental introduction to Flow Visualization as a team, this assignment was once again to find an inspiration in real life, capture it in an image or video, and report on the fluid mechanics and physics at play with your teammates. Daniel Luber, Tiangen Ge, and I decided that the first team event should be something fun to get to know each other better. Daniel brought up the idea of experimenting with "Oobleck" as a first investigation. Oobleck is a classic experiment in elementary school all the way through high school, and even college students can have fun with it. It gets its name from Dr. Seuss' *Bartholomew and the Oobleck,* where Oobleck was a gooey green character who fell from the sky. Oobleck is a non-Newtonian fluid: it can be poured like a liquid but it acts as a solid when a shear force is acting on it.

So that's what my team decided to do. The three of us got together at Daniel's apartment on the night of October 12, 2016; Daniel had bought two boxes of cornstarch to make a large vat of oobleck. He also bought two sets of four different water-based food dyes to color the oobleck. As it turns out, in order to get an image I was truly proud of, it took more time and effort than originally expected. We were all inspired by the color trails that dripped down white posters. They looked like colorful stalactites. However, multiple trials (unedited image of multiple trials shown in Figure 2) proved that the medium of oobleck varies in viscosity depending on how much food dye was added in the shot glasses.

Figure 2: Multiple Trials of Oobleck Dripping Down the Poster Board

The Physics and Fluid Mechanics behind the Image

As the flow visualization was composed of items made in Daniel's kitchen, so too was the flow apparatus used to capture the image in Figure 1. The required ingredients to recreate this image are two boxes of cornstarch, tap water, and the eight food dyes mentioned before. Mixing the two cornstarch boxes with water in a large mixing bowl by hand, gently and thoroughly to ensure the uniformity, was absolutely the fun part of capturing the images (this is shown in Figure 3). The fluid also has the color-absorbance properties due to the water-based type of dye. The oobleck was ready when we could still mold it with our hands, but it would run back into the bowl if undisturbed for a few seconds. In fact, we could punch the fluid in the bowl and it would barely give, but we could easily scoop it out if we did it gently. The ratio of cornstarch to tap water ended up about 1.5-parts cornstarch to 1-part water, but the measurements were not exact as we added a little extra water at the end and food dye watered it down as well.

Figure 3: Mixing Oobleck by Hand

The oobleck was then balled up by hand and placed in shot glasses, where we added the food dye to each individual shot glass. Most colors took anywhere from three to six drops of dye to get a pure, strong color. The dyes were added by hand to start, then we found that using a knife to scoop the oobleck from the bottom of the glass worked well to dye the entire shot glass volume uniformly. Many shot glasses were filled with different color creations throughout the night. The common colors that were reused multiple times were yellow, green, neon green (which looked like Nickelodeon's green slime), red, orange, blue, and purple. To create the image seen in Figure 1, the green, red, orange, and yellow shot glasses were poured onto the top of a poster board, laid horizontal on Daniel's breakfast bar. Then just a pinch of more green, yellow, blue, and raspberry were placed in the middle of the larger puddles of colored oobleck. After a few moments of drying (about 1 to 2 minutes depending on the trial), the poster was flipped up at a sixty-degree angle, allowing the oobleck to drip down the poster board. This set-up can be seen in Figure 4. When capturing the image, the poster board could be placed back down on a flat, level surface. Since the oobleck is a fluid (it reacts continuously to a shear and does not return to its previous shape, as a solid would) the flow will "freeze in time" for the photography. This technique was used for some pictures, but not all of them. Figure 4b shows Daniel capturing a close-up of the board while it is still upright (at the aforementioned 60^o angle) on a chair.

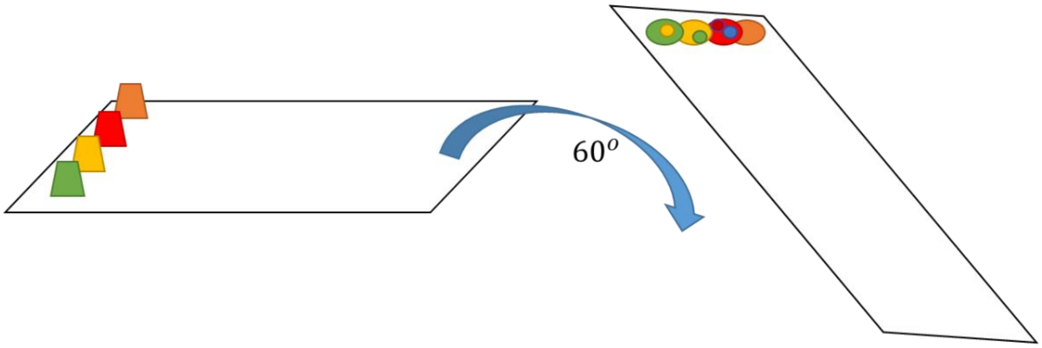

Figure 4a: Flip Shot Glass of Dyed Oobleck onto Poster board

Figure 4b: Daniel Capturing a Close-up Shot with Above Lighting

In order for this flow visualization to occur, two main physical phenomena must be at play. First, viscosity is the internal friction in a fluid at the molecular level due to inelastic collisions. A fluid with high viscosity is thick like dish soap or honey. Meanwhile a fluid with low viscosity is thinner and "runny," like water out of the tap or chicken broth. Oobleck can act like both, depending on the forces on the fluid. As previously mentioned, we tried playing with the oobleck by punching it in the bowl and it would barely give. But we could easily scoop it out if we did so gently, then we could ball it up. When the ball was allowed to rest in our hands it would get runny again. These are the characteristics of a non-Newtonian fluid. In continuum mechanics, a Newtonian fluid is one in which the viscous stresses arising from its flow, at every point, are linearly proportional to the local strain rate. Strain rate is the rate of change of a fluid's deformation over time. The plot in Figure 5 shows the stress versus strain of common fluids.

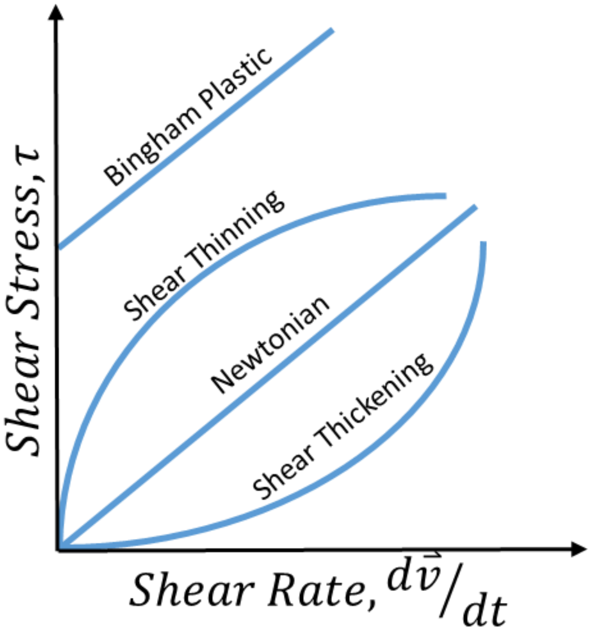

Figure 5: Shear Stress vs. Rate of Non-Newtonian Fluids

According to Newton's Law of Friction, the oobleck shears under the gravitational forces, and begins to flow down the poster board. The shear stress from gravitational forces can be found using the following equation:

$$\tau = \mu \frac{d\vec{v}}{dy}$$

Where τ is the shear stress for a fluid with given viscosity μ, acted on causing the fluid to flow with velocity $\vec{v}$, giving the velocity gradient $d\vec{v}/dy$ as the shear rate. Back to Figure 4a, if that position (the poster board at a 60º tilt) is held, it allows the very top layer of oobleck to flow down the board due to a shear force of gravity. For many fluids (Newtonian fluids), the viscosity is constant resulting in the straight line for a slope. However, a non-Newtonian fluid has interaction between large particles resulting in the nonlinear relationship between shear rate and shear stress, as observed. Viscosity of a fluid is given by Power-law, or the Ostwald de Waele relationship, as:

$$\mu_{eff} = K\left(\frac{du}{dy}\right)^{n-1}$$

Where μ_{eff} is the effective viscosity for a Newtonian or non-Newtonian fluid as a function of K, the material constant for the fluid known as the flow consistency matrix. For Newtonian fluids, n=1 which forces the shear rate to go to 1, resulting in viscosity as a material property only. If a material is shear thickening, also known as a dilatant, then n is greater than 1. This results in the viscosity being a function of both the material property and the shear rate. In fact, assuming n=2 for oobleck, the equation for shear stress becomes:

$$\tau = K\left(\frac{du}{dy}\right)^{2}$$

Which matches the parabolic relationship shown in Figure 5. The other key to capturing these images was using water-based dye in the oobleck. Oobleck itself is water-based, which is what makes it so easy to clean after making a huge mess. Using water-based dye ensures that the dye molecules go wherever the oobleck flows. This is what creates the fantastic marbling and flowing in Figure 1, where the different colored oobleck puddles run down the board together but do not have enough time to disperse or mix together.

Visualization and Photography Techniques

The visualization technique was a simple one, utilizing common materials in the kitchen to capture the colorful dyes dissolved in oobleck flowing down a tilted board. The cornstarch was mixed 1.5:1 with water from the tap to decrease the viscosity and form the non-Newtonian fluid described previously. The oobleck was placed in shot glasses where the colors were added, then they were poured on a poster board and set on a chair with tape to hold the board at the appropriate angle. For lighting, the overhead dining room bulb was left on. I did not use the camera's built in flash.

As for the shot itself, the photograph was taken with a Canon EOS 7D digital camera. The camera was held about even with the poster, and a foot to the side of the poster to capture the image shown. The camera was zoomed in slightly, then the boundaries cropped out in Photoshop. The aperture was set to a larger f-number of f/5.6 to allow more light to enter the camera since the sources of light were not bright compared to natural sunlight. The shutter speed was set to 1/30 sec to try to allow as much light in as possible while also reducing the amount of blur from hands moving while holding the camera. We had a tripod for capturing images, but this one was not taken on the tripod. And lastly, the sensitivity was set to a pretty high ISO of 1000. The high sensitivity resulted in the addition of noise (as seen in the bottom left corner of Figure 6 below, which is the original). Once the picture was taken, it was edited in Photoshop. As previously mentioned, the borders were cropped to center the marble fluid flow while limiting the distractions in the image. The color contrast was then edited using the curve adjustment tool. Each end of the RGB color spectrum, the whites and the blacks, were brought in to fully utilize the entire range of contrasts. Then one end of the blue curve was adjusted to enhance the coloring of the blue and green streaks in the oobleck on the white and shadow-black background. I used the magic wand tool to highlight and basically delete the background, leaving only the dripping oobleck and the shadows on the board to enhance the contrast just a little more. Last, the sharpen tool was used to highlight the edges just slightly. The original image snapped by the camera on the evening of October 12th, 2016, is shown in Figure 5a. The Photoshop color curve of the RGB color scale is shown in Figure 6b, and the color curve of the blue color scale is in Figure 6c. All of these edits result in the final image, again shown in Figure 1 on the first page.

Figure 6a: Original Image

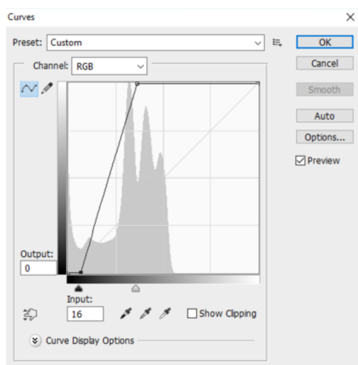

Figure 6b: RGB Color Curve Adjustment

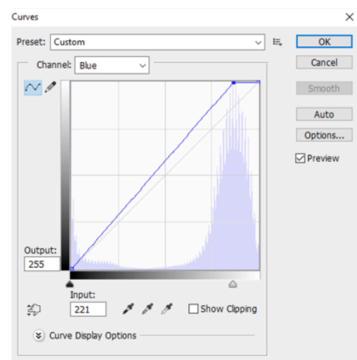

Figure 6c: Blue Color Curve Adjustment

Conclusion

In the end, the image reveals the true visual beauty in common materials. It was also a perfect first team assignment as we all had the chance to get messy playing with oobleck then capture fantastic images the same night. The inspiration for this image came from Daniel's idea to play with some oobleck. When the shot glasses of dyed oobleck were poured on the poster borad and allowed to run with gravity, the colors mixed and swirled better than any of us imagined. I like the fact that this image was composed with oobleck and the stalactite look of the dripping oobleck flowing to create fantastic marbling and color contrasts. I also like the fact that the paths are mostly parallel and very simple. Overall, the intent of this image was fulfilled.

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