Flow Visualization of Water Droplets on a DVD

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Introduction

Figure 1: Water Droplets on a DVD

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. Since Daniel Luber's schedule would not match up with Tiangen Ge and me over the two weeks between team assignments, we decided that the second team event should be something simple that we may be able to do alone. Tiangen and I still got together to take pictures on the evening of Halloween. We were looking for inspiration, and found it on the home page of flowvis.org. Figure 2 shows a screenshot of the image on the scroll of the main page, unfortunately the original photographer is unknown. The image shows multiple rainbows of light diffracting by a broken compact disc.

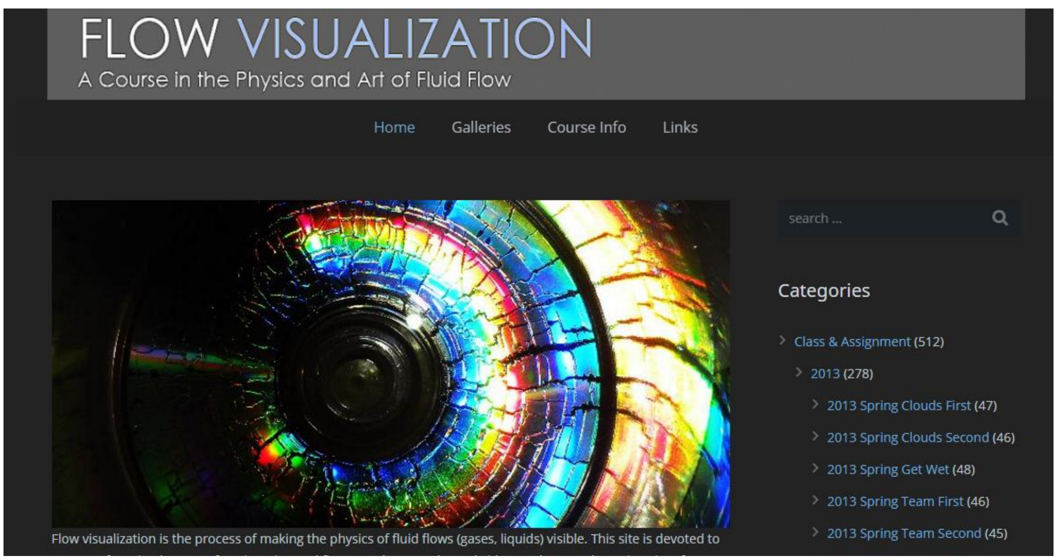

Figure 2: CD Image on the Front Page of Flowvis.org

Tiangen and I decided to do something similar. However, we wanted to use droplets of water to bead up and expose all of the colors in reflected and refracted light rays as well. The liquid droplets would act like prisms. As previously stated, Tiangen and I got together at my apartment in Family Housing, just North of University of Colorado's main campus, on the night of October 31, 2016. I asked the receptionist at the Dean's Office of the College of Engineering and Applied Sciences at CU if they had any extra CD's, likely used for storage devices years ago. Luckily, the receptionist went to a storage closet and came back with a blue DVD that was blank and not needed by anyone for other purposes anymore. Tiangen bought a set of four different water-based food dyes to color the water (I did not use dyed water in my final image, but a few trials were done with blue, green, yellow, and red water to see if the rainbow effect still occurred). 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 both inspired by the array of colors being diffracted by the DVD (in a blue base due to the initial blue hue of the DVD's surface) and on the surfaces of the prismatic water droplets. They looked like colorful globes racing on a surface of rainbow fire. The mirroring effect even seemed to put the water droplets in motion, causing one student to comment that the image reminded him of Rainbow Road in Nintendo's *Mario Cart*.

However, multiple trials proved that the final image depends on light source and orientation as well. The final edited image shows two main water droplets, one in great focus (shifted off to the bottom-right of the image and containing tiny mineral particles from Boulder, Colorado's tap water), and the other is larger, centered, and just slightly out of focus. The larger, centered water droplet looks to have a tail extending off to its right, in total having the resemblance of a tadpole. Hence, the single sentence post online, "Lit water droplets on a DVD create a colorful tadpole." There is also a "flame" of visible diffracted light on the surface of the DVD. There are multiple physical phenomena at play in the image creating the rainbows on the surface of the DVD and rainbows on the prismatic water droplets.

The Physics and Fluid Mechanics behind the Image

The white light of my LED headlamp, like all light, consists of a mixture of the colors of the rainbow. They can be split using a CD or DVD, which will reflect different colors of light in different directions. If you look at different parts of the DVD the light is bent at different angles, thus you see the different colors. This is because DVD's have grooves and ridges in them. Surface roughness with regular patterns, on the same order of magnitude as the wavelengths of incident light, cause diffraction to occur.

This phenomenon is prominent at the bottom of Figure 1, where a rainbow of colors looks to form a flame on the surface of the DVD, where there is no liquid present. Surface roughness causes diffuse reflection. When the roughness has a regularly repeating pattern, with pattern separation on the same order of magnitude as the wavelength of incident light, the resulting phenomena is diffraction. A CD contains two layers of plastic protecting a thin layer of aluminum on which is stored the actual information, stored in pits in the aluminum organized in a series of concentric circles. The lines of shiny aluminum reflect well and the lines of pits reflect poorly in comparison. Because the gaps between the pits are very close together (650 nm for a

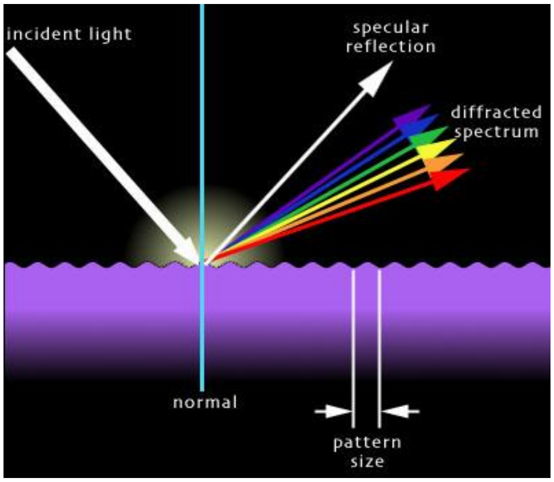

Figure 3: Surface Roughness Causes Diffraction, courtesy of http://emerald.tufts.edu/

4.7 GB DVD, according to Cal State Fullerton, Department of Physics), a distance equivalent to the wavelength of visible light which ranges from about 400 nm for violet and 700 nm for red, the reflections will interfere with one another. The incident light is broken up into two components: a specular component and a diffracted component. The specular component obeys Snell's Law of reflection, and will behave similarly to the incident light, shown in Figure 3b. The diffracted spectrum is broken into a rainbow, with the light of shortest wavelength (violet) located closest to the specular reflection, which is also shown in Figure 3b. To determine what angles the various colors are reflected off of the DVD's surface, the following equation is used:

$$\theta_r = sin^{-1}\left(\frac{m\lambda}{d} - sin(\theta_i)\right)$$

Where θ_r is the angle that a diffracted component of wavelength λ escapes a surface, away from the incoming incident angle of light from θ_i. The DVD's properties are captured in d, the separation of grating elements, and m, an integer starting at 1 and continuing on for the number of cycles present. Each color has a different wavelength (ranging from 400 nm for visible violet light to 700 nm for visible red light), but the same incident angle. Thus, if the original incident angle is known, the diffraction can be calculated for each color. The color scale is continuous, however, which creates the effect shown at the bottom of Figure 1. There is only one set of colors in Figure 1, thus $m = 1$ for the entire piece. Table 1 shows the diffraction angle for the basic colors in the rainbow away from an incident angle of $\theta_i = 30^o$.

Table 1: Diffraction Angles for the Colors of the Rainbow

Color	Wavelength (λ)	Diffraction (θ_r)
Red	700 nm	35.2^o
Orange	620 nm	27.0^o
Yellow	580 nm	23.1^o
Green	520 nm	17.5^o
Blue	480 nm	13.8^o
Indigo	430 nm	9.3^o
Violet	400 nm	6.6^0

These values would match the diffraction shown in Figure 3 and the explanation given by Professor Peter Wong, as well as the color streaks shown at the bottom of Figure 1, the edited image taken for Flow Visualization, second team project.

This, however, does not completely describe the prism effect of the water droplets. First, in order for the water droplets to hold their shape and act as prisms, their surface tension had to hold the water as a droplet. Surface tension consists of both cohesion and adhesion. Cohesion is the intermolecular (hydrogen bond) forces of water holding one water molecule to the next.

Water has a high cohesion value for surface tension of 72 mN/m at room temperature, which is the highest among common non-ionic, non-metallic liquids. Adhesion, on the other hand, is the attraction forces between the water molecules and the DVD. The adhesive force that the liquid exerts on the object it is in contact with, in this case a DVD, is dependent on the length of contact according to the equation:

$$F = \gamma L$$

Where γ is the coefficient of surface tension, equal to 0.072 N/m from before. The larger water droplet (that forms the tadpole-look with its tail) was in contact with the DVD for approximately 1 cm (or 0.01 m). This results in a force on the DVD from the surface tension of the water droplet of 0.00072 N. Now that the surface tension is known, and is steady enough to hold the water droplet together on the surface of the DVD, the water droplets both magnify the rainbow color rays and slightly act as prisms. In optics, a prism is a transparent optical element with flat, polished surfaces that refract light. The traditional geometrical shape is that of a triangular prism with a triangular base and rectangular sides, hence the name “prism.” At least two of the flat surfaces must have an angle between them. However, not all optical prisms are in the shape of geometric prisms. Prisms can be made from any material that is transparent to the wavelengths for which they are designed in this case water and the surfaces with angles between them are on a round droplet.

Visualization and Photography Techniques

The visualization technique was a simple one, utilizing common materials like a DVD to capture the colorful light diffraction then water droplets acting as prisms reflecting and refracting the light as well. Water droplets of various sizes were positioned on the DVD then the DVD was rested on the kitchen floor. For lighting, the overhead fluorescent bulbs were turned off to reduce the reflection of the room on the mirror-like surface of the DVD. An LED camping headlamp was held about 6 inches off to the left of the image, and about a foot off to the side of the DVD which provided the primary light. I did not use the camera phone’s built in flash.

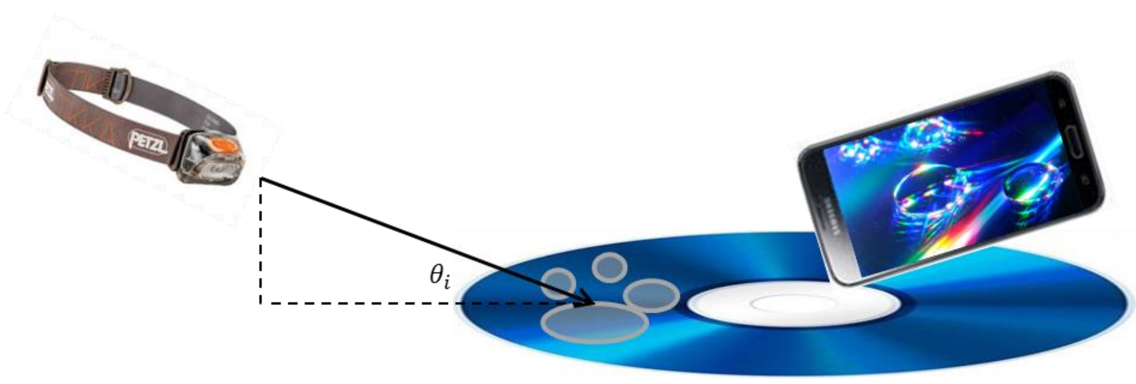

Figure 4: Experimental Apparatus

As for the shot itself, the photograph was taken with a Samsung Galaxy S5's camera. The camera on the Samsung Galaxy S5 is one of the more powerful on the market, according to techradar.com. It features an iso-cell unit that offers 16MP pictures. Many trials were taken with my Olympus point-and-shoot digital camera as well (which is only 12 MP by comparison), but my favorite image just so happened to be shot with my phone. The camera was held above the DVD, pointing back at a 30^{o} angle. The camera was zoomed in slightly, then the boundaries cropped out in Photoshop. The aperture was set to a smaller f-number of f/2.2 to decrease the direct light coming into the camera from the headlamp, and enhance the rainbow spectrum of colors. 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. Since this was captured on a camera phone, it was not taken on a tripod. And lastly, the sensitivity was set to as low an ISO as possible: ISO-80. The low sensitivity resulted in very little addition of noise, which was key to producing this image on a dark background. The original image is shown below in Figure 5, fully resolved at 3264 pixels by 1836 pixels.

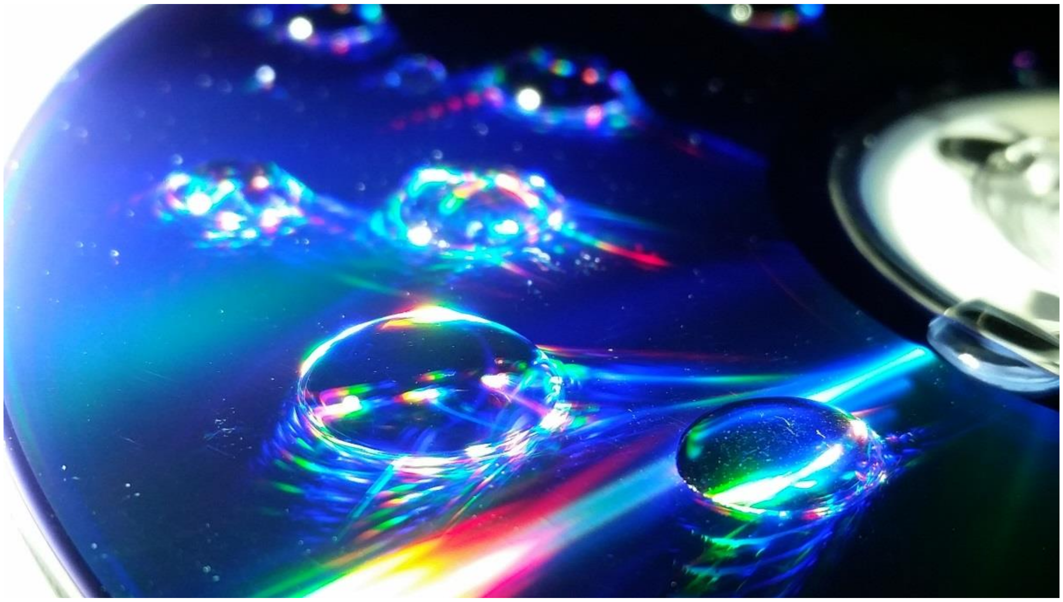

Figure 5: Original Image Taken on October 31, 2016

Once the picture was taken, it was edited in Photoshop. As previously mentioned, the borders were cropped to center the droplet that looks more like a tadpole with the shimmering tail, and the droplet in best focus is off center (about one-third up the image, and one-third from the right edge), while also limiting distractions and background in the image. The color contrast was not edited using the curve adjustment tool at all, the colors are all natural. I used the magic wand tool to highlight and basically delete the center hole of the DVD. Then I matched the top corner with one of the darker blue streaks in the top right corner of the edited image (shown in Figure 1). Clone Stamp was used to erase the larger dust particles, primarily on the left side of the image. Last, the sharpen tool was used to highlight the edges of the water droplets just slightly.

Conclusion

In the end, the image reveals the true visual beauty in common materials. The inspiration for this image came from Flow Visualization's website, but Tiangen and I put our own twist on the project. When the water droplets dripped off my fingers and onto the DVD, then the headlamp set at a 30^{o} reference angle, the diffraction of light off the DVD and reflection and refraction of light through the water droplets create the colorful, futuristic look of Figure 1. In fact, the mirroring effect nearly sets the droplets in motion, like spaceships over a rainbow road. I like the fact that this image was composed with only tap water and a DVD, creating fantastic color contrasts. Overall, the intent of this image was fulfilled.

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