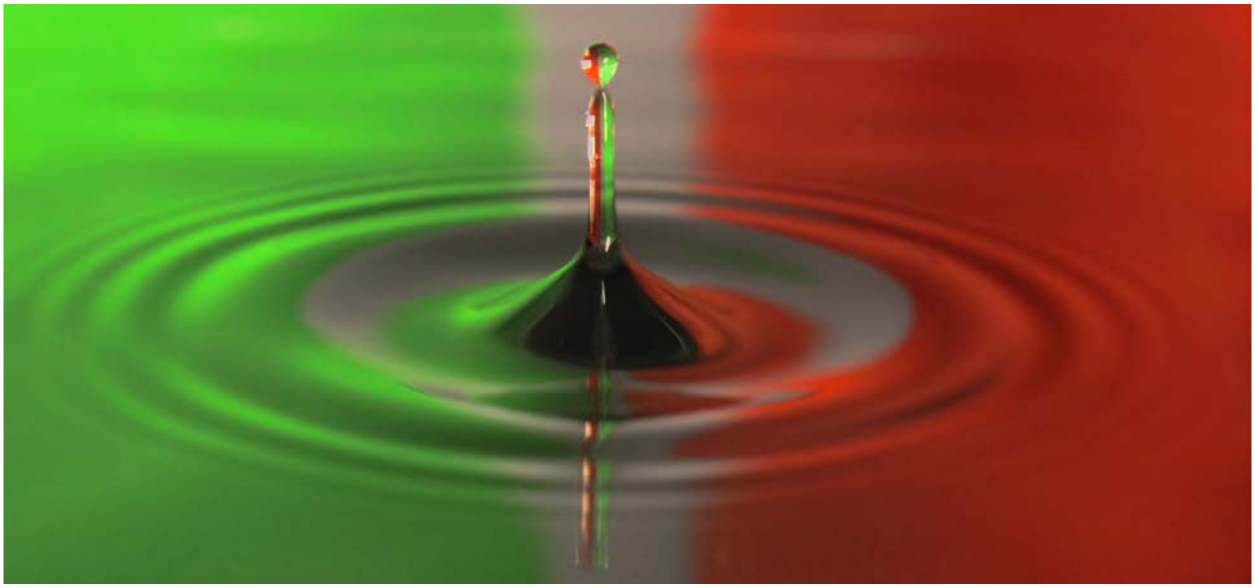

“Irish Luck”
Dan Maguire
MCEN 5151

Introduction

The picture captured above was taken for class MCEN 5151, Flow Visualization, offered at the University of Colorado - Boulder. This first project, “Get Wet”, is an introductory assignment where the students are able to take any “flow object” and capture it in a photo or video. It’s a fairly open assignment without much limitation so the picture/video can be any number of items. The assignment also allows students to introduce themselves with their personal cameras, understanding the basic capabilities that their camera offers such as aperture, shutter and ISO proficiency. The two main objectives that the image is meant to capture is that it demonstrates some physical flow phenomena and that it’s a good, quality picture that offers some artistic relevance. For my final image, I decided to capture the moment where a drop of water hits a fluid surface. I felt this project offered enough difficulty in both image timing and setup that it would allow me to really “get my feet wet” with what this class is meant to be about. I also felt there was enough physics behind the image that a quality assessment could be made in what’s actually taking place in the picture.

Setup

The setup of this experiment was actually the most time consuming part of the project. I not only needed to determine what the best way of taking the photo was, but I also needed to gather all the right materials in order to conduct the testing correctly. The lighting became the most difficult part of the actual setup because getting enough light to capture a visually accurate picture proved to be a challenge. I ended up purchasing a set of two 500W halogen lights that were propped up on a stand. These became an essential piece of the setup although just one 500W bulb proved to be enough light to get a satisfactory image. Another important piece of the setup was getting the drop of water to hit the pan in a very consistent location so I could focus the camera in a specific spot. Using specific camera settings in the manual mode along with needing to focus on a very specific area forced me to set up something that allowed the drops to hit in the same spot. To do this I gathered a few things from around the house including a couple chairs, a pole, some duct tape and a bag of water. The bag had a small hole in the corner which allowed for a very consistent drop of water to fall into the pan at a fairly quick rate. To get a different perspective for light I used a few different colors of construction paper and placed them as a backdrop, focusing the light on those pieces of paper. The spot in which the water was dropping was 7" away from the lens, and the camera was placed on a tripod in order to try and stabilize the image as much as possible. A sketch of this setup, along with a picture, is shown below in Figure 1.

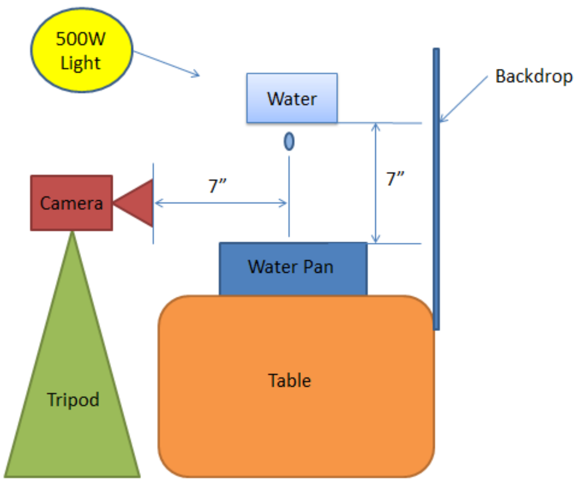

Figure 1: "Get Wet" Setup

Phenomena

The main phenomenon that is captured within the image is called a Worthington Jet. The reasoning for the formation, the size and the height of the Worthington Jet is due to the size of the drop, the height at which the water is dropped and the surface tension value of whatever the drop is hitting. A common approach of describing the splash characteristics in a situation like this is either using the Reynolds or Weber number, although in the more recent studies the Weber number seems to be the more common approach. The most basic way in describing the Weber number is that it's a comparison between the inertial forces of the drop and surface tension forces of the water within the pan [5]. The equation that calculates the Weber number is below.

We = $\rho V^2/\sigma L^{-1}$ = inertial force / surface tension force

ρ = density of water, V = velocity of drop, L = diameter of drop, σ = surface tension of water

Per a source from Georgia State University, the surface tension of water is 1.605×10^{-1} lb/in [4] and the density of water is 3.613×10^{-2} lb/in^3. The velocity of the drop is easily calculated using the height of the setup (7") and the gravity constant of 386.088 in/s^2, yielding 73.5 in/s using the equation $v=\sqrt{(2*g*h)}$.

The final value used in the equation is the diameter of the drop. Since the drop was photographed at multiple frames when hitting water, I was able to measure the diameter of the drop in relation to the size of the image being photographed and compute a drop diameter of 0.125". Putting all these values together results in the following calculation:

$We = \rho V^2/\sigma L^{-1} = 3.613\text{x}10^{-2}\ lb/in^3\,(73.5\ in/s)^2\ /\ 1.605\text{x}10^{-1}\ lb/in\ (1/0.125\ in) = 152$

In a paper by Meaden & Meissen they correlate the Weber number with a few different splash characteristics, impact & spread velocities along with spread factors. In the report they range the Weber number from 100 thru 300 for water and record the splash tendencies from both a velocity and splash spread standpoint[1]. As you'd expect, the higher the Weber number (the higher inertial forces) the larger the spread velocity and spread factor[1]. This correlation is fairly obvious and one that I'd expect in my own setup if I started to increase the height of the drop and measure the differences in the size of the splash and height of the Worthington Jet.

When the drop initially hits the water pan it leaves an empty crater that can vary in size depending on the drop parameters and liquid surface. This crater then quickly closes back up on the top surface, subsequently developing a large jet that shoots out from the center of the drop impact zone – the Worthington Jet. A photo taken during my experiment, and shown below in Figure 2, shows the crater that is formed on the top surface of the water pan. This gives you a sense of how large a crater is formed from just a 0.125" diameter drop impact and why the final Worthington Jet caught in my final image can become so large. Once again, ranging the size of the drop and height at which it's released would be an interesting experiment to see how large, or small, these craters end up becoming. At smaller heights, the Worthington Jet won't form due to a lack of inertial forces overcoming the surface tension forces.

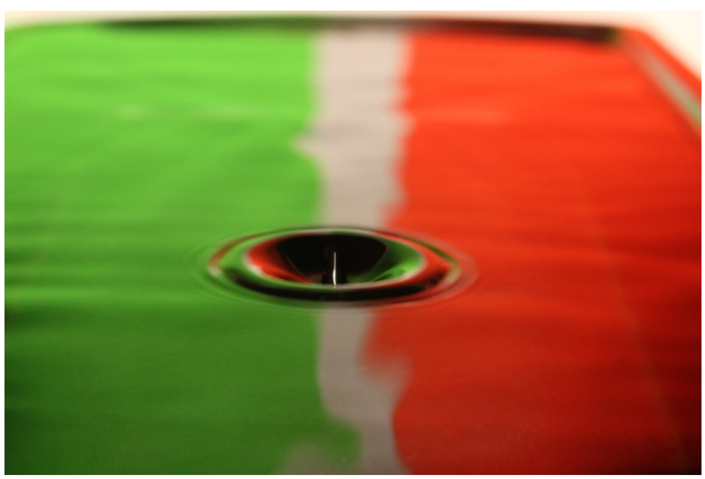

Figure 2: Initial Crater Formation from Drop Impact

In a study conducted by Gekle & Gordillo, their research estimated the jet to be roughly 20 times faster than the initial impact speed [3], giving a sense of how quickly the crater fills back up, with the potential to reach some incredibly high speeds depending on how high the drop is being released from.

Visualization Technique

The main visualization technique used in this setup was the impact of a water drop hitting a dish full of water, and capturing the splash that happens the moment the two collide together. I mostly focused on the Worthington Jet that is formed just after impact, but I also wanted to bring in multiple colors in order to really bring some life to the image. In order to do this, the lighting used needed to be vibrant and bright enough to really catch the details of the jet that is formed moments after the two collide. To accomplish this effect a 500W halogen light was used and shined directly on the backdrop which included a white board with a taped bright green and orange piece of construction paper. The light of that backdrop reflected in the water pan and proved to be an adequate amount in order to capture the phenomena. The built in flash on the camera was not used in this image, just the continuous light of the halogen lamp.

Photographic Technique

The main purpose of this setup was to get the impact of the drop just as it hits the water, although we're talking about milliseconds from a timeframe standpoint, so it took numerous shots in order to get the final image. The settings of the camera became an important aspect when taking the picture. The manual mode was selected on my DSLR Canon T2i camera in order to adjust both the aperture and shutter speed while using the manual focus setting on the lens itself. Numerous angles, physical distances, zoom distances and camera settings (aperture, shutter speed, ISO) were experimented with in order to come up with the best image. The table below is a breakdown of the final settings that were used for the final image. The combination of an aperture setting of F8.0 and an ISO setting of 2500 (chosen automatically) allowed for a clear, well focused image in the space I was working with. I chose a shutter speed of 1/160 in order to "freeze" the drop after it's formed the Worthington Jet, and not have blurred image. I had to focus, or zoom, in on the area using the maximum capability of the lens of 55 mm while using the manual focus in order to bring the image into focus which was roughly 7 inches away. The image was cropped down to a pixel size of 4616 x 2144 in order to center the main focus of the image, the Worthington Jet and ripples that are formed when the drop hits the water initially. The image was in a .png format initially but was brought into GIMP and darkened slightly in order to bring out more of the colored background, so it's not as washed out. The final image was exported as a .tif image. Both the original and final images are shown in Figure 3 below.

Table 1: Camera Settings

Setting Description	Setting Value
Aperture	F8.0
Shutter Speed	1/160
ISO	2500
Zoom/Focal Length	55mm
Original Pixel Size	5184 x 3456
Cropped Pixel Size	4616 x 2144
Object/Image Size in Original Photo	3" x 2"

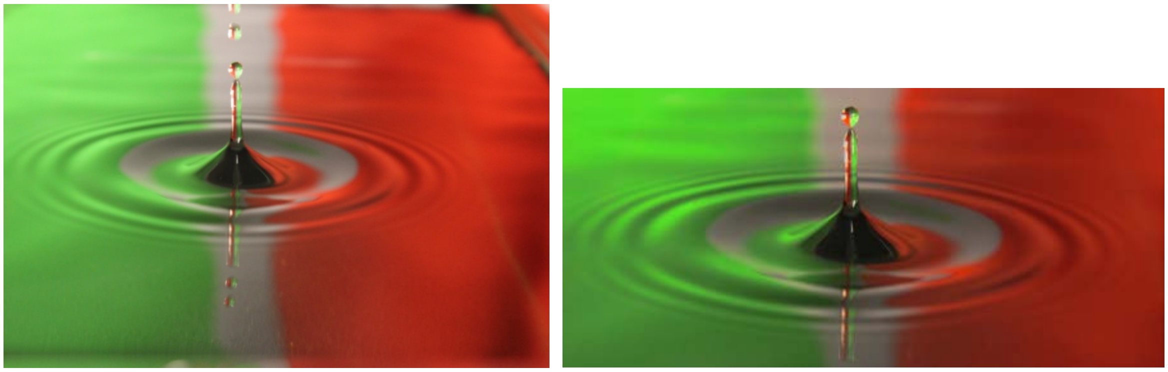

Figure 3: Original and Final Image

Conclusion

I thought the final image really captures what I initially intended to do, photo a Worthington Jet. I also believe I brought a little creative flare into the image by using three different colors in the background, and centering the drop directly in the middle of the three. I really like the ripples the initial impact makes, showing the symmetry that the image has relative to the center jet. The waves are really smooth and refined looking; an aspect that I did not think would be captured in my initial visions of how the image would look. The one aspect of the image that I wish would've turned out a little better was the glare that's picked up along the edge of the left side of the jet. Unfortunately, due to the sensitivity of the lighting this showed up a little in a small portion of the image, which is part of the reason I decided to darken the image a little more after bringing into to the GIMP software package. Because of this issue, that's the one aspect I would concentrate on a little further; pay more attention to the lighting in the room and adjust as needed. The only other thing I would like to explore a little further would be catching more "moments" of the jet, and really adjust the drop heights and temperatures of the water or surface the water is hitting, and see how the affects the images. As pointed out in the research done by Kandlikar, Steinke, & Singh the surface temperature can really affect the splash and spreading characteristics. While varying the Weber number, along with the surface temperature, the droplets took on different characteristics that were captured throughout the report[2]. Although these were captured while the droplet was hitting a hard surface, I believe researching the same phenomena with a droplet hitting a liquid surface would be interesting to note what differences took place while varying the Weber number and surface temperatures. I took hundreds of pictures in various camera settings, angles and lighting, but changing the physical setup would be an interesting follow-on to this project.

References:

[1] S. Gekle and J. M. Gordillo, *Generation and Breakup of Worthington Jets after Cavity Collapse*. Part 1. Jet Formation, J. Fluid Mech. 663, 293 (2010).

[2] Kandlikar, S. G., Steinke, M.E., and Singh, A., *Effects of Weber Number and Surface Temperature on the Boiling and Spreading Characteristics of Impinging Water Droplets,* Paper No. NHTC01-11672, Proceedings of NHTC'01 35th National Heat Transfer Conference June 10-12, 2001, Anaheim, California (2001)

[3] Meaden, M., Meissen, E., *Dynamics of Successive Drop Impacts on a Solid Surface*, (2011)

[4] Nave, R., *Surface Tension,* http://hyperphysics.phy-astr.gsu.edu, retrieved from http://hyperphysics.phy-astr.gsu.edu/hbase/surten.html

[5] Ngo, C.C., *Fluid Mechanics – Theory*, ecourses.edu, retrieved from https://ecourses.ou.edu/cgi-bin/ebook.cgi?doc=&topic=fl&chap_sec=06.3&page=theory