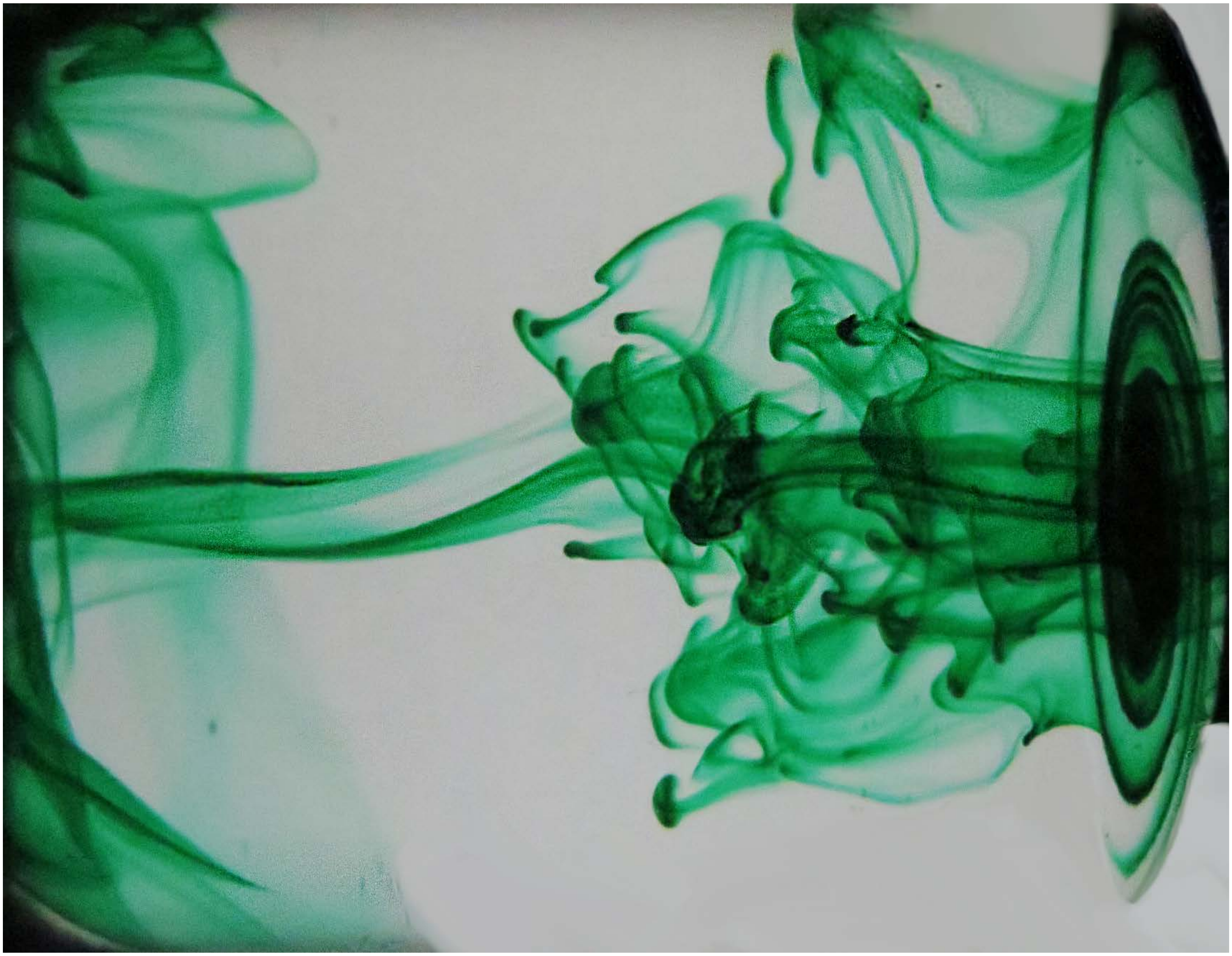
Analysis of Dye Dispersion Through Water



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Get Wet Assignment
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Introduction

The flow patterns generated by dye dispersing through water generally provide some very beautiful images. For this experiment, green dye was dropped into a clear glass of water in order to observe its visual effects during its diffusion in water. The purpose of this was to capture the unique flow patterns resulting from the dye spreading through the water, as well as to create an intricate image with an artistic flow path. Several dye colors were used in order to create several different flow patterns. However, due to the low light intensity of the light source as well as the somewhat intricate effect generated by the green dyes, the chosen photo utilized only green dye with water. The following paper describes the experimental setup, technique, and flow analysis involved with the flow seen in Figure 1 below.

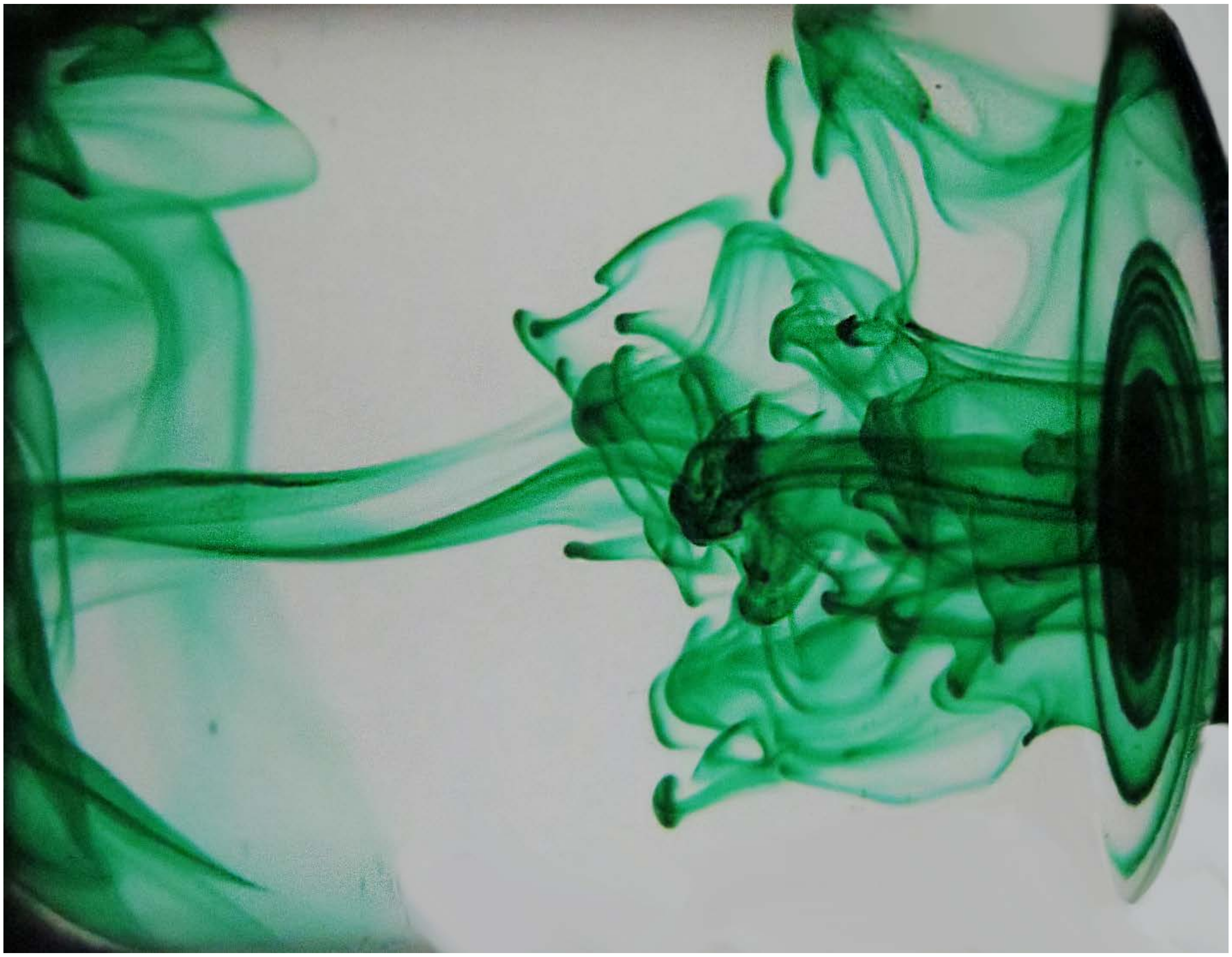

Figure 1-Application of Green Dye to Normal Tap Water in a Glass

During the execution of this experiment, several team members in addition to myself were involved in the equipment setup, dye application, cleanup and reset operations, and camera operation. Consequently, I would like to acknowledge Kristopher Tierney and Will DerryBerry for helping me capture this wonderful image.

Experimental Setup

This experiment utilized a 19 cm high glass with a diameter of 4.2 cm to contain the fluid environment used to apply the dye. In order to ensure that the pictures were as clear as possible, the glass was cleaned beforehand and dried carefully to avoid creating a water stain whilst removing fingerprints. For the purposes of lighting, a computer screen full screened to a white background was used as a backlight for the glass. See Figure 2 below.

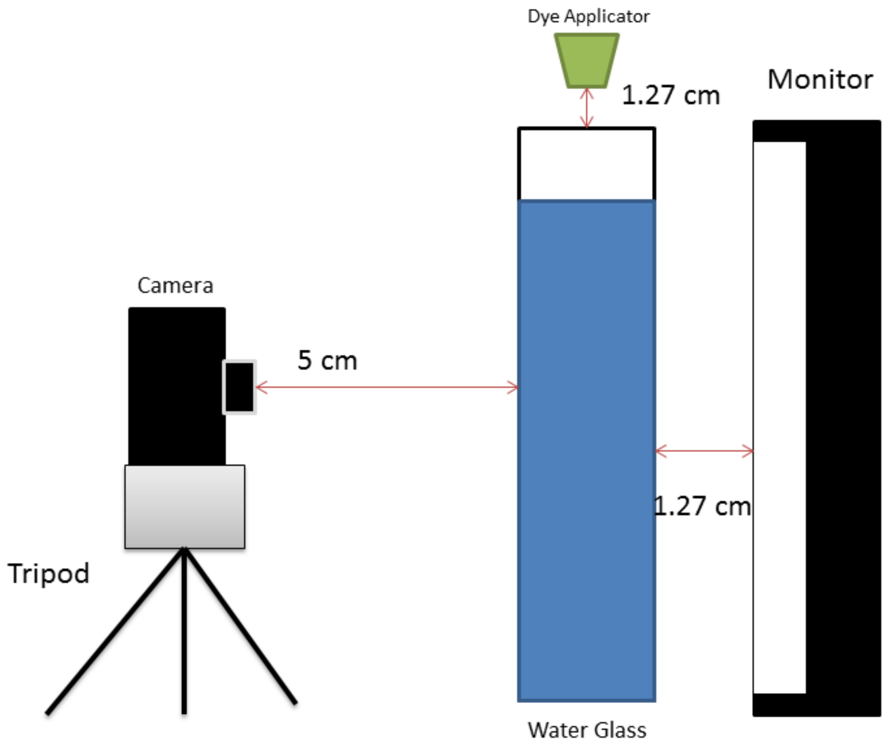

Figure 2-Schematic of the Experimental Apparatus

While this did provide an ample amount of light to catch the flow effects, a brighter and higher quality screen would have created a much sharper contrast for the experiment. All other light sources such as hallway lights and sunlight were obscured through a nighttime photo session and a curtained room.

Physics of Dispersal and Diffusion

The water used for the experiment was approximately 10^{o}C. Consequently, it can be inferred that this water's density was 999.8 kg/m^3, with a specific volume of 10^{-3} m^3/kg, and a specific heat of 4.193 kJ/kg-K [1]. For general reference purposes, the Reynold's number of the experiment was calculated using Eq (1) as seen below [6]:

$$Re = \frac{U_d R}{v_{water}} \qquad \text{Eq (1)}$$

The velocity of the drop settling, U_d was estimated outside of the experiment by marking two points on a glass (relatively close to each other), and dropping dye into water at approximately 10^{o}C. Using a basic stopwatch, an overall estimate of the drop velocity was around 0.120 mm/s. For R (the radius of the drop), the standard drop's radius was approximately 0.2 mm. Consequently, the following calculation was performed (v_{water}= 1.307 x 10^{-6} m^2/s):

$$Re = \frac{(0.120\frac{mm}{s})(0.2mm)}{\left(1.307\frac{mm^2}{s}\right)} \qquad \text{Eq (1)}$$

$$Re = 0.2$$

It is important to note that a Reynolds Number of 0.184 is below the threshold needed for a drop to keep a spherical shape during diffusion. While not completely clear, it is possible that the whirlpool at the top of the photo was created due to this Reynolds Number. However, the main points of interest of the photo are contained within what occurs after the whirlpool. Within this experiment, the dye's primary method of dispersal through the water was diffusion, a transport phenomenon that results in the dye dispersing and then mixing with the water. As a result, the following aspects of diffusion that will be addressed are the thermal energy and its relation to diffusion, the randomness of the diffusion, and overall, the chemical and thermodynamic mechanism that governs this diffusion itself.

During diffusion of dye into water, the temperature of the water can reduce or accelerate the diffusion through Fick's First Law of Diffusion, as seen below in Eq (2).

$$J = -D\frac{\partial \phi}{\partial x} \qquad \text{Eq (2)}$$

Eq (2) above primarily describes the diffusion flux, or the amount of substance per unit of time that will move through an area during a given time interval [2]. It is important to note that the constant "D" from Eq (2) is the diffusion coefficient or the diffusivity of the system. Consequently, if the same system was to be subjected to an increase in temperature, the diffusion coefficient would change and consequently, the amount of substance per unit time would increase. This is governed by the Stokes-Einstein Equation as seen in Eq (3) below:

$$\frac{D_{T1}}{D_{T2}} = \frac{T_1}{T_2}\frac{\mu_{T2}}{\mu_{T1}} \qquad \text{Eq (3)}$$

Where T1 and T2 denote the temperatures of the solute and solvent, D is the diffusion coefficient at those corresponding temperatures, T is the absolute temperature, and μ is the dynamic viscosity of the solvent [3]. As a result, the diffusion of the experiment was deliberately slowed using colder water as to minimize the motion blur physically and to capture the diffusion more clearly.

Another important aspect of diffusion is the randomness of the diffusion itself. During the experiment, it was clear that no level of consistency of experimental execution would ensure the same pattern. During the diffusion of the liquid, there were several different forces acting on the particles of food dye in addition to hydrostatic forces. As the dye began to flow through the glass, gravity directed the molecules to the bottom, which in turn, concentrated them at the base of the apparatus [4]. However, there was also an opposing force to the motion of the dye in the form of friction, which originated from the water contacting the dye particles [4]. As a result, while the force of gravity was relatively constant, the location of the resulting concentration gradient depended primarily on where the majority of the particles fell at the bottom of the glass. Additionally, molecular collisions at higher energy states resulted in more randomized patterns. [5] In this sense, friction as well as molecular collision were the primary factors that resulted in a randomized flow pattern as these interactions governed the landing of the particles of dye, and furthermore, the location of the concentration gradient along the bottom of the glass.

The final aspect of diffusion that will be analyzed is the concept of a concentration gradient, and more importantly, how this affects the flow pattern. As seen in Figure 1 above, the dye had a tendency to cluster together. In other words, the dispersing of the dye appeared to be a single body, but with different spreading points. This was due primarily to the concentration gradient created by the dye, which was briefly addressed earlier [4]. Figure 1 above shows two areas of high concentration, the top as well as the bottom. When the dye was first dropped, the dye spread throughout the surface of the water and did not penetrate the water surface. However, gravity eventually pulled the dye through and allowed it to flow to the base of the glass. Note, as stated earlier, that the diffusion constant, force of friction, and molecular collision served to direct the flow as it proceeded to the base [3] [4]. Once the flow had begun to create a concentration gradient at the bottom, the dye began to move against gravity, shifting particle mass from the dye back towards the top [4]. At this point, the particles were being driven back and forth by the concentration gradients between the top and bottom of the glass, creating the channel like flow pattern between the top and the bottom. In addition to this flow, as gravity continued to pull the dye downward, additional channels formed, causing the umbrella like pattern that was observed in Figure 1.

Visualization Techniques

To produce the image indicated in Figure 1, a water medium was chosen due to its consistency as well as inert state. Glasses were obtained by a team member, with water being supplied from the ITLL Laboratory Sinks (with temperature of 10^oC). However, due to the sink water containing excess gas, the water contained several bubbles that interfered with the visibility of the dye application. Consequently, in order to remedy this problem, tongue depressors were used to clear the bubbles through a scraping motion of the sides of the glass. The experiment itself took place in an ITLL study room at approximately 5:30 PM. Shades within the room were used to obscure sunlight and the room lights themselves were shut off to avoid washing out areas of the image.

Lighting was provided primarily from a monitor, which was full-screened to a white background. This created a very sharp contrast to the solution as the backlight maintained the water's transparency. However, it is important to note that the backlight also revealed several temporary imperfections of the glass and water, such as bubble content, fingerprints, as well as residuals fibers from towels that had been used to dry and clean the glass. In addition, the brightness of the monitor was adequate, but not optimal as certain trial runs revealed that the monitor would be unable to completely light the flow observed as the dye diffused through the glass. All other sources of light were eliminated from the environment in order to compensate for the brightness of the monitor.

Photographic Techniques

The image was captured using a Canon PowerShot SX280 HS Digital Camera. In order to capture the photo, only a quarter of the glass height was used, with an additional 2.5mm removed as the glass was not filled all the way. Consequently, the height of the photo was approximately 4.5 cm. The width was the diameter of the glass, which was 4.2 cm. For the length between the camera and the apparatus, the glass was approximately 5 cm away from the camera lense when the photo was taken. During the photoshoot, the camera was set to a focal length of 4 mm, an exposure time of 1/2000 sec, and an ISO setting of 3200. The field of view was determined due to a limitation from the height of the monitor screen in addition to the limited length of the table. However, the field of view was also fine-tuned to ensure the most significant portion of the flow was captured. As a result, a significant part of the glass was not included within the photo as it detracted from the more exciting aspect of the dye diffusion. The exposure time was chosen to compensate for the monitor backlight and to ensure that a sufficient amount of light would enter the lense such that the flow characteristics of the darker green dye would be captured. The focal length was chosen in order to limit the amount of background that would appear within the photo (objective was to fill the photo with as much of the experimental setup and limit the angle width). As for the ISO setting, 3200 was chosen as it eliminated some of the grain within the image as well as compensated for the brightness of the monitor. However, despite the settings, certain imperfections remained within the photograph itself. Figure 3 below is the unedited image. Dimensions in pixels are 4000 x 3000 pixels.

Figure 3- Unedited photo of green dye dispersing through water

Due to the loss of the monitor's brightness towards the bottom of the image, the shine from the top of the glass, as well as the darkened spot at the top of the fluid, I decided to crop the photo between the darkened line at the base of the photo and the dark ring at the top. In addition, the background at the side of the photo was removed as it detracted from the flow itself. As stated earlier, the backlight from the monitor did not provide the brightness needed to fully resolve the flows of the dye as it converged to the bottom. Consequently, Photoshop CS5 was used to change the contrast of the photo as well as the saturation. Additionally, the dark ring towards the top of the photo as well as the shine spot was removed in order to direct the focus towards the flow. For the final changes, the sharpen tool was used to clarify certain blurred areas of the photo such as the whirlpool at the top in addition to the misty area at the bottom. Figure 4 below is the final edited image. Dimensions in pixels are 2384 x 1849 pixels.

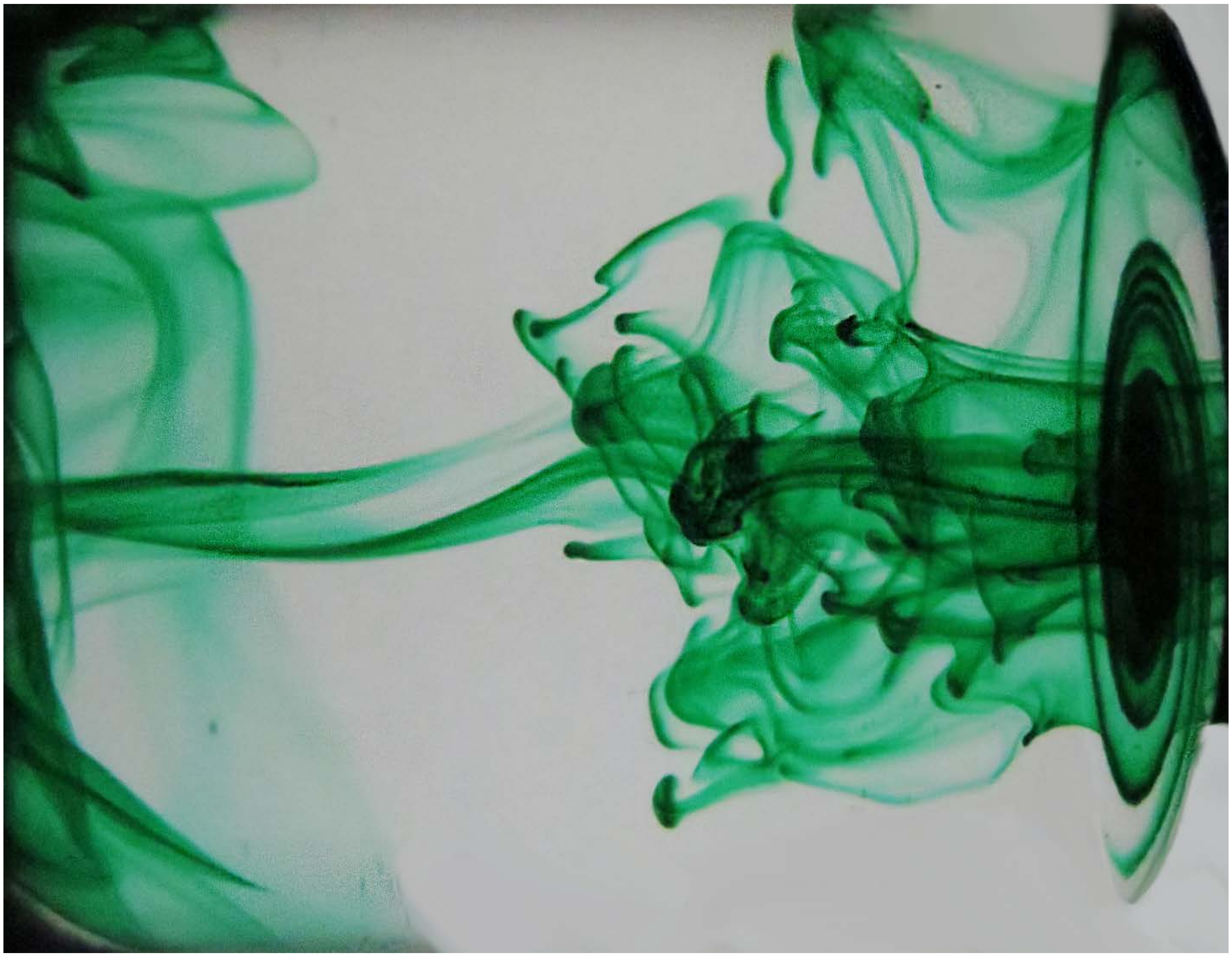

Figure 4- Final edited image of dye diffusing through water

Overall Analysis

As a general summary, the image revealed the somewhat randomized yet strikingly graceful flow of the dye dispersing through the water. I was especially surprised at how well the concentration gradients' movement was shown within the photo itself. Furthermore, the "diverging" nature of the drops from the top to the bottom as well as the single "channel" like stream allowed me to visualize the frictional effects that determine how the dye traveled to the bottom of the glass. The whirlpool effect at the top also provided the illusion that this photo was more complex than a simple dye dispersion experiment. However, I did not like the extremely dark line that lined the whirlpool. It seemed to be a result of the glass itself as opposed to the actual physics of the experiment, which disappointed me a little. In addition, in order to compensate for the monitor's insufficient lighting, the central flow was slightly obscured by the darkness of the dye itself. Regardless, I was very happy to have captured the complex flow of dye dispersing into water. My original intent was more artistic than technical as I wanted to find a very complex flow pattern within a simple setup. Furthermore, I was surprised I was able to generate a whirlpool as several attempts at the same experiment did not always create a clear and artistic whirlpool. In terms of questions for the project, I would like to find out what caused the whirlpool itself as the entire system was stationary, except when the dye was dropped. Furthermore, it looked as if it was confined only to the surface suggesting surface tension was a factor in its formation, in addition to Reynolds Number as mentioned above. However, I still could not physically determine what forces had caused this spinning effect. Consequently, I would have liked to research this phenomenon further. Some aspects I would like to improve would be the apparatus itself. While the glass was tall and did provide a very good medium in which to drop the dye, I would have been interested to see what a larger diameter glass would have done to the flow pattern. Additionally, I would have liked to use a different monitor that contained a higher LCD brightness setting. I feel that in some way, if the backlight had been brighter, I would have been able to resolve the whirlpool and central flow pattern behaviors and comment on them more thoroughly.

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