Use of Flow Visualization Projects to Personalize Introductory Fluid Mechanics For Students

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Introduction

Introductory Fluid Dynamics classes are often viewed by engineering students as one of the most challenging courses in the curriculum. The course is content heavy with a strong reliance on complicated equations which can make the material appear dry and distant to many students. Beyond that, introductory fluids is a required course for many engineering disciplines and has a wide range of student interest levels. At Clarkson University the introductory fluid mechanics class includes students from the Mechanical and Aeronautical, Civil and Environmental, and Engineering and Management departments. Engaging students by making the subject personally relevant is challenging given these boundary conditions. Personal connection is needed to actively engage the students in their learning. This paper describes a flow visualization project that is designed to personalize fluid mechanics by having students take and reflect on a picture of a flow field that they find "interesting". The results of this project is assessed and the outcomes described based on four criteria: 1. <u>Originality</u> of the picture; 2: aesthetic <u>Quality</u> of the picture; 3. <u>Clarity</u> of the flow visualization; 4. seriousness of the <u>Reflection</u>.

The Navier-Stokes Equations are the fundamental equations of motion for a fluid. These can be expressed in variable form for an incompressible Newtonian fluid as:

$$\rho(\frac{\partial}{\partial t}(\vec{V}) + \vec{V} \cdot \nabla\vec{V}) = -\nabla P + \rho\vec{g} + \mu\nabla^2\vec{V} \qquad (1)$$

These equations are 2^{nd} order, non-linear differential equations, which is conceptually overwhelming. Even when these equations are simplified, it is difficult to translate the mathematical expression into a mental picture of the physical reality. This is true even for many faculty who have worked with these equations over the course of a career. Alternate analysis methods that are taught, such as integral analysis, are useful engineering tools but they too often remain just equations, with mysterious variables and meaning to the students. These mathematical and engineering descriptions are critical to problem solving, but what is often lost is an understanding or appreciation of the fluid motion. This is unfortunate because the very nature of the fundamental equations allow for the rich and beautiful motion of fluids in the world around us. It is also unfortunate because students, especially those who do not see the personal relevance of fluid mechanics, often fail to connect the course material to their own lives and experiences.

One way to make the subject of fluid mechanics more accessible is by using flow visualization. When a flow field can be seen, the complexity and beauty becomes apparent. This in turn moves the subject from mathematical to aesthetic allowing for students to make not only personal but also emotional connections. It is these personal and emotional connections that provide critical intrinsic motivation for students. This paper describes a flow visualization project given to students in an introductory undergraduate fluid mechanics class. This project was designed to promote a personal connection with the broad subject of fluid mechanics and thereby encourage students to become engaged in the course material.

Project Description and Metrics

Students were asked to take a picture of a fluid flow that they found personally “interesting”. The requirements for the picture were that: 1. The fluid phenomenon must be visible in the picture; 2. It was a picture they took, or that it was a picture they were in; and 3. The picture should be interesting to them. The project description and discussion of the project in class emphasized that “interesting” was a value judgement left to each student. This was done purposely to give the students space to personalize the project. Examples of flow visualization images were included in the course content throughout the semester. This was done first to motivate each lecture and demonstrate concepts, but also to provide examples to the students on what “flow visualization” was or could be. Some of the example images were scientific (e.g. visualization of experimental or computational flow fields) while others were from daily experiences (e.g. vortices observed in sauce while cooking). A variety of example images were chosen to purposely give examples of “staged” flow visualization where one might work purposely to see a flow phenomenon, and natural/opportunistic flow visualization where one might notice something in the world that is interesting, beautiful, etc. in the moment. Students were told that both approaches were acceptable as the real criteria was that they found the picture interesting.

The students were asked to provide a two page report and an original copy of the image at the end of the semester. Within the report the students had three tasks. First, students were asked to describe the flow field in the picture, including a sketch of the flow field (e.g. schematic vectors or streamlines). It was stressed that these were sketches and they were interpretations of the flow shown in the image. Second, students described how the image was staged and flow was made visible. For example, images of environmental flows may have natural seeding like water vapor in clouds, while experiments may have had dyes added. Finally students were asked to reflect on the picture and answer two questions. Why did they find the picture interesting? And, what question did the picture raise in their minds? Students were told that either technical or personal answers to both reflection questions were acceptable. The reflection was structured with this openness so that students who were not naturally excited about the topic could tie it to some personal experience. For example, a picture taken while hiking with a friend or sibling might be personally relevant because of the personal nature of the experience and may also contain some interesting phenomenon (e.g. a waterfall). The purpose of the second question was to encourage the students to expand their reflection beyond what was directly shown in the image. This reflection was also modeled during the semester when the example flow visualization images were presented to the class. Examples of both technical and personal reflections were given by the instructor.

The project was assessed using four metrics: *originality* of the flow, aesthetic *quality* of the image, *clarity* of the flow phenomenon, and quality/seriousness of the *reflection*. Each metric was assigned an integer score of 0-4 in those categories by the course instructor. The originality score was based on how unique the subject of the image was. For example, common subject that students see frequently in their daily lives are rivers and streams. These projects score low in originality. A subject that was shown as an in class example may score midlevel in originality if only one or two students recreated this example. However, if a student added to or changed an in class example their project scored higher in originality. Quality was assessed based on aesthetics of the image. Was it in focus? Was the image well composed? Was the image carefully staged and taken? Clarity of visualization was determined by how well the intended flow phenomenon was shown in the image. Could the flow feature be seen clearly or at all? Finally, the reflection score was based on how deeply and authentically the students answered the two reflection questions. The category assessment scores were made independently. For example, a student may have chosen a common (scored low on originality) flow, say milk being poured into coffee to show mixing. However, that student make have taken a well composed, artistic picture resulting in a high image quality score. That same image may have also scored low on clarity because the coffee obscured the details of the mixing but scored high on reflection. The assessment of the project described in this work is focused on the correlation between those metrics, as well correlation of those metric with final course grade. Note that the metrics were assigned without knowledge of the course grade so that bias was avoided. Course grades were added to the analysis after project metrics were assigned. A total of 157 students were enrolled in two sections of the class during the 2019 Fall semester. Both sections were taught by the author.

Examples of Student Work

In this section of the paper examples of student images are presented. The images were chosen to illustrate the variety of images that ranged in originality, quality and clarity. Figure 1 shows common subjects (low originality) that students staged to complete the project. By far the most common staged subject this year was a magnetic stirring rod in a beaker. The submission date of this project coincided with a laboratory that was being conducted in the Mechanical and Aeronautical Engineering lab class that utilized a magnetic stirring rod. This presented an easy, last minute subject for the flow visualization project that required very little preparation on the part of the students who chose it. In general the images were of low to moderate quality in terms of the aesthetics, and the seriousness of the reflections followed this general trend. Another common theme for the flow visualization images was, unsurprisingly, coffee. The two samples of this topic in Figure 1 show the range in image quality. The image of the coffee pot was poorly composed and the flow was difficult to observe from the image. In contrast, the image of the coffee cup with the spoon was more esthetically composed. The background was interesting, the spoon added depth to the image, and the instabilities caused by the stirring were clearly visible due to the contrast between the dark coffee and white cream. Mio jets were another popular, easily accessible subject. Again the two example images in Figure 1 show the range of image quality, and ease of viewing flow patterns. Finally, a more thoughtful common image type is flow from a faucet. The example shown in Figure 1 is the use of a spoon to deflect the stream and turn it into a sheet that breaks up into drops. That image was moderately well composed. The sponge on the back of the sink could have been removed, and the flow could have been in better focus to improve the aesthetics.

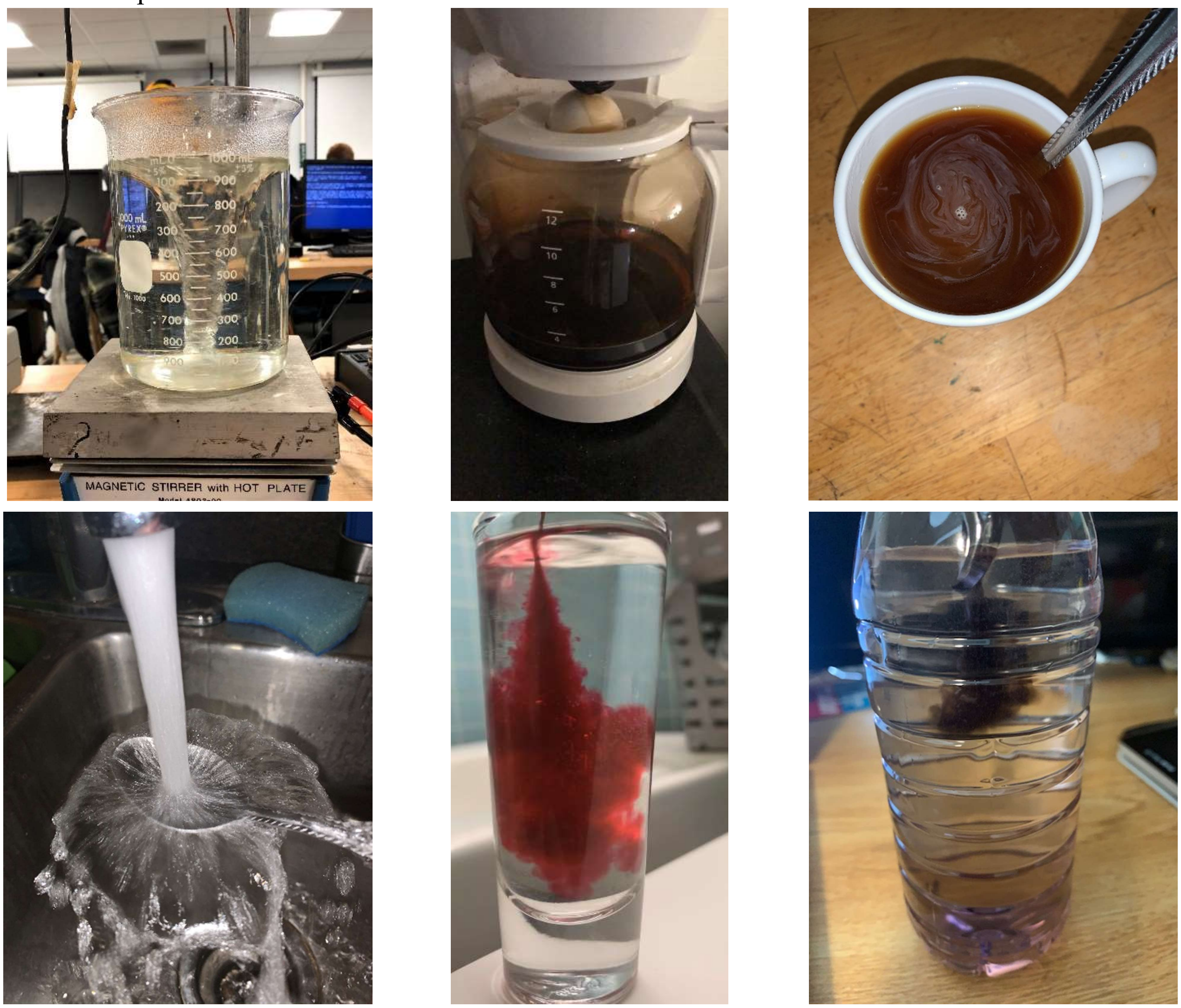

Figure 1: Common Staged Image Subjects

Many students chose to take use pictures taken from observation of the world around them, rather than from staged experiments. These images commonly focused on flow in streams, waterfalls and dams. While the topical areas of these images were common, the subjects and composition of the images showed variety. For example the three images of waterfalls included one that is a local hiking and swimming location (top middle), one from near the students home (top right), and Niagara Falls (middle left). The image of the dam in Figure 2 is one of the local dams near campus in Potsdam, which was a fairly “easy” subject, but the image was well composed and thoughtful. Typically these images score low on the clarity of the flow phenomenon due to the lack of control over the flow and the reliance on natural visualization. This trend was not always true. The included image of the rock in the stream was nicely composed and the flow phenomenon was clearly shown by the surface waves upstream of the rock.

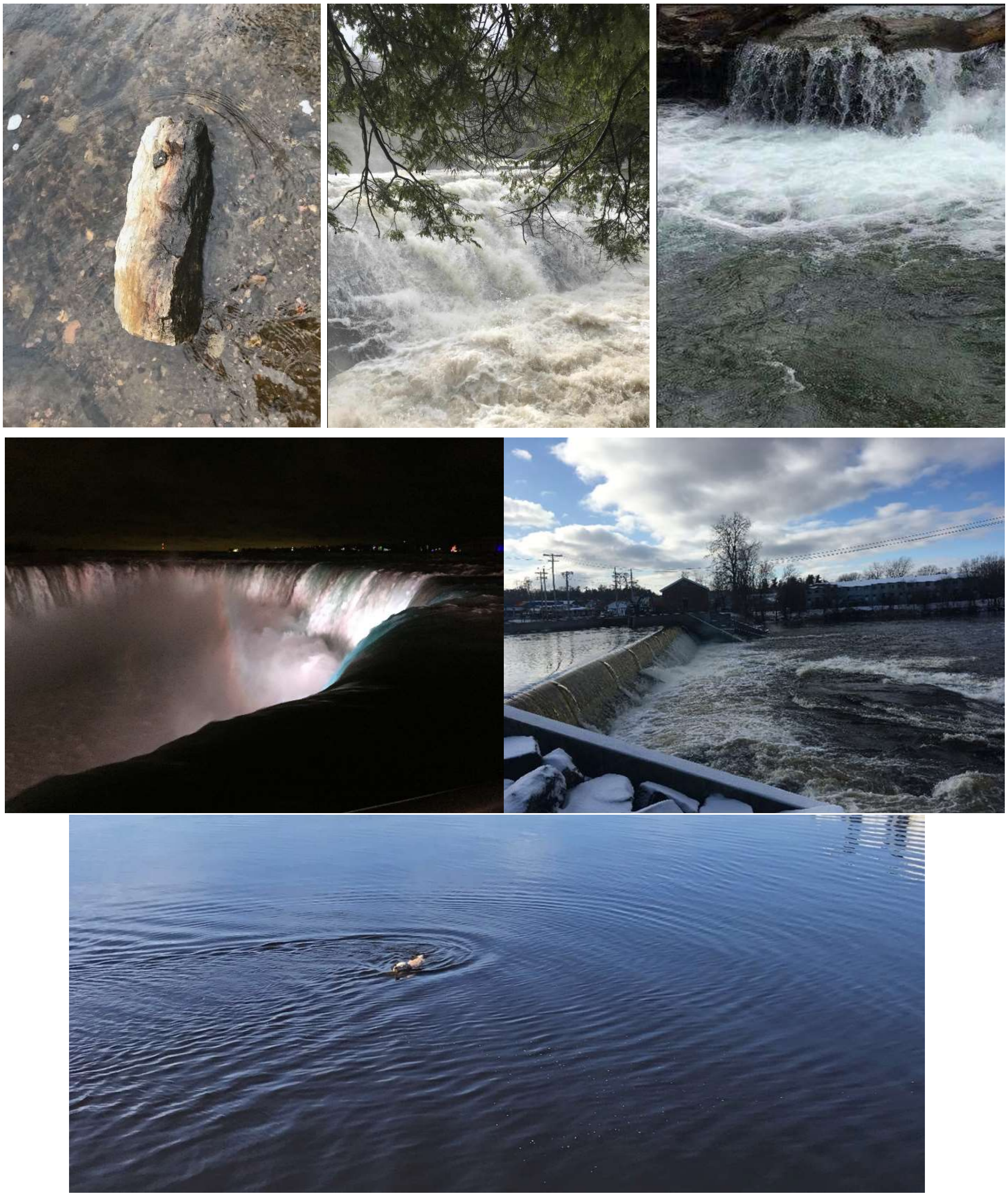

Figure 2: Common Natural Image Subjects

Examples of student images with high originality scores are shown in Figure 3. Students whose images scored high on originality tended to fall into one of two categories. First, they observed a flow that was naturally formed, was interesting to them and they had the opportunity to take the picture in the moment. For example, the image in the upper left hand corned of Figure 3 was taken when a student was having their car washed in an automatic car wash. The student noticed the sheet of water running off the hood and the ripples that formed in the sheet and then was able to capture the image in the moment. Secondly, the students had a definite subject for their image either based on a personal experience, or based on something that was shown or discussed in class. The middle left image in Figure 3 shows "needle ice" where ice forms upward by drawing liquid from the ground. The student who took this image is an avid hiker and had seen these formations. That student, motivated by past observations, used this project to learn more about that phenomenon. Examples of ideas that were taken from material discussed in class were the crown splash (middle top), hydraulic jump (right top) and jumping liquid jet (bottom left). The jumping liquid jet image was intriguing in that the student had a pencil in the lower right side of the picture with the words "see something" printed on the pencil. The author does not know for sure if this was purposely done, but the coincidence would be remarkable if it was not. The bouncing ball (bottom middle right) was a students rework of the classic "bouncing milk drop" experiment. They remaining example images were independently generated by the students. Of particular note are the tear drop bubble (lower right) and the water into soap (middle) which were images that had never been turned in by students during all of the years this project has been run.

Finally, images taken by students that had personal meaning or connection. The three landscape images were of Denali in Alaska (upper left), Mt. Daniel in Washington (middle right) and a waterfall in Ireland (lower left) were taken on trips that the respective students had taken with family or friends. Reflections were consistent that the images were chosen because of personal importance placed on those trips. The picture of the bubble ring in the pool (upper right) was taken by a student who was a competitive swimmer. This student's reflection stated that the subject of the image was chosen because of the connection between a personal passion and the course material. The image taken on the middle right was of vortex rings created during the start-up of a John Deere tractor on the student's family farm. The reflection here indicated that the student had seen these vortex rings and noticed them, but now had technical understanding to put them in context. The bottom middle image was taken at that student's family hunting camp in the Adirondacks. The project inspired that student to come to office hours and talk about ideas the student had about improving the fresh water supply at the camp. Finally, the middle left image is of soap film across the opening of a travel mug. That student was a non-engineering student who had chosen to take the fluids class because the material was interesting. That image was taken when the student saw the soap film while cleaning the bottle and was inspired by the colors and structures shown.

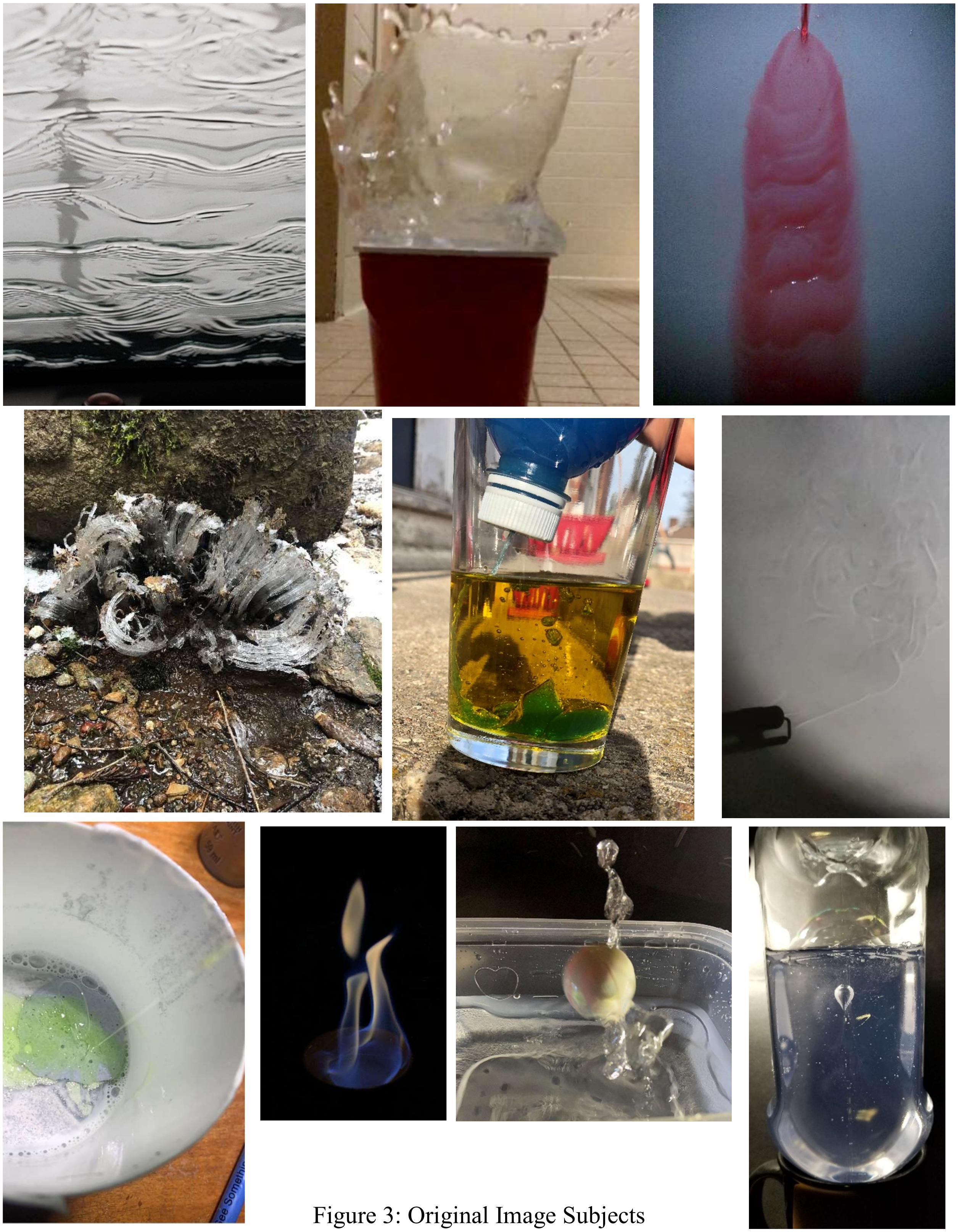

Figure 3: Original Image Subjects

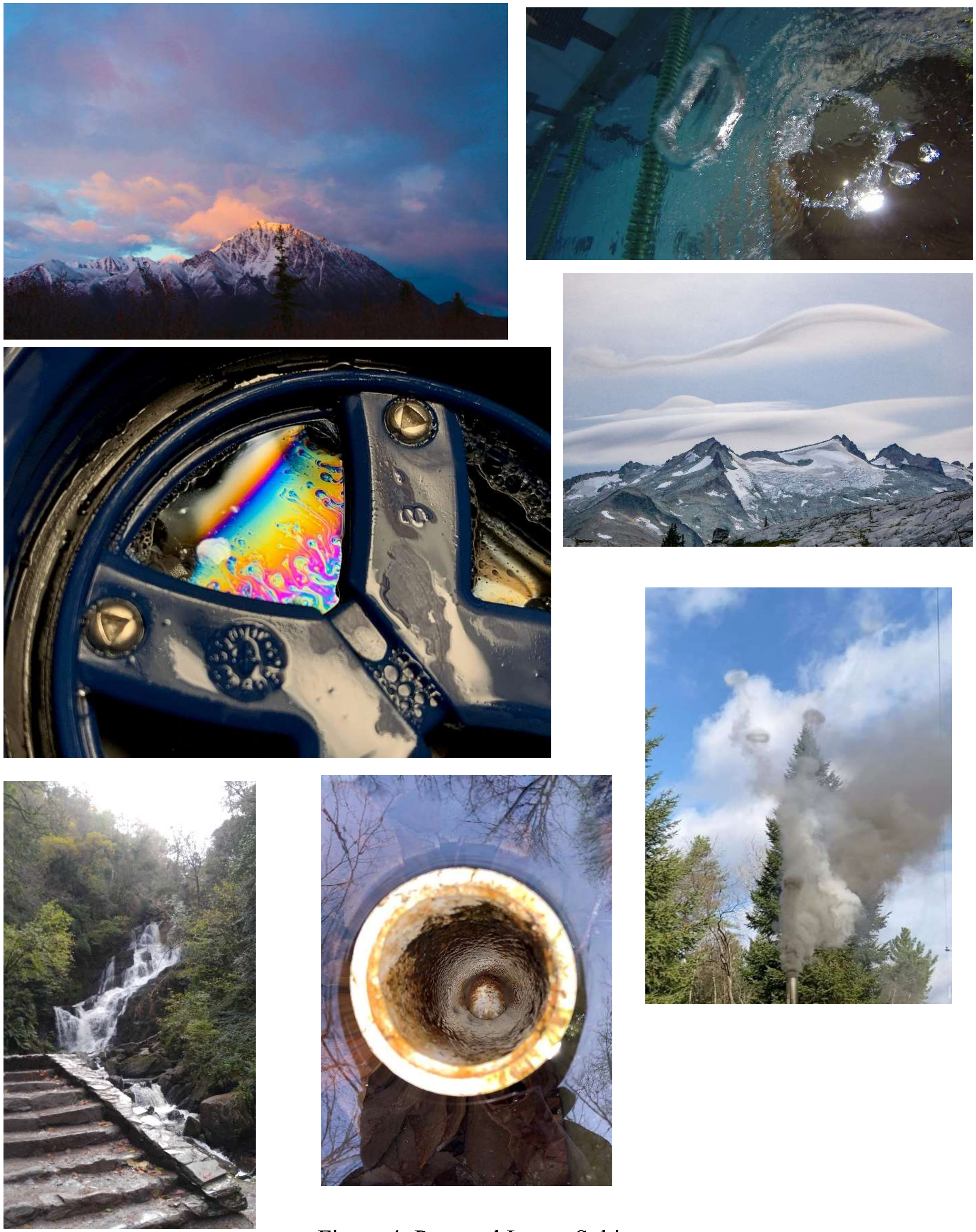

Figure 4: Personal Image Subjects

Assessment of Project Outcomes

Assessment and analysis of the project outcomes are now considered. Figure 5 shows the breakdown of the natural versus staged images. Roughly 66% of the students staged or purposely set-up the scene they imaged while 33% of the students used natural settings. Broadly speaking the natural setting were chosen due to a personal experience while the staged images were chosen because of a personal interest. The average and rms values of the metric scores are presented in Figure 6 for all students and also broken down based on natural and staged scenes. The originality score was found to be the lowest of the four metrics investigated. This was not surprising given that the students were new to the subject and did not have sufficient background to find original ideas. However, the average score of 2.8 was still well above the numeric average of 2 indicating that the majority of students came up with original or somewhat original subjects. The variation in the originality score for the staged projects was significantly higher than for natural subjects indicating students pick both easy and original phenomena to image. The highest mean score was found to be for the reflection metric (3.4) indicating the students were able to express why the image was interesting to them personally and that they were able to form a question based on the subject they chose. The most significant variation between the natural and staged subjects came in the image quality which showed a mean value of 3.2 vs 2.8 in that category. This was likely because the student who chose to stage images would have had to put effort into composing the image to score high in this metric, whereas the natural images subjects required less purposeful composition. Further, the natural images tended to be inherently more aesthetically interesting.

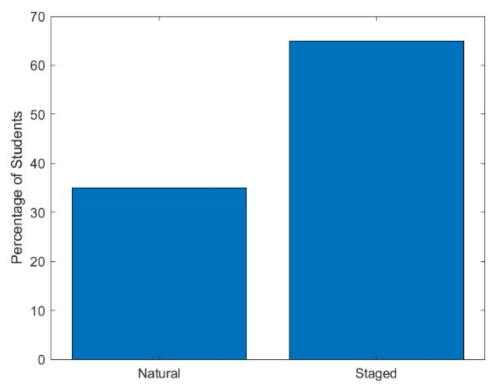

Figure 5: Breakdown of Project Subjects

The data were then sorted by each metric score to investigate relationships between metrics. For example, the data were sorted by the originality score and the mean scores for the other metrics (quality, clarity, and reflection) were determined. It is noted that the sample sizes for each mean as the distribution of scores were not equal, Figure 7. These distributions show that the only metric with a statistically significant number of students with a score of 1 was found for originality. The number of students whose images scored lowest for originality was still relatively low and indicative that relatively few students picked “easy” or “obvious” subjects. In fact, approximately 30% of the students picked highly original subjects. Image quality showed a peak at a score of 3 indicating that the majority of students turned in images that were well composed (quality score of 3 or 4). The distribution of students for these two metrics, which could be interpreted as "effort", indicated that the majority of students put effort into choosing a subject and executing the image. The clarity of the visualization of the flow was evenly distributed showing a wide range of success in this category. This was not surprising given the students were novices at fluid mechanics in general and flow visualization in particular. Approximately 80% of the students received a 3 or 4 on the reflection metric. Again, most students appeared to take the project either seriously or somewhat seriously.

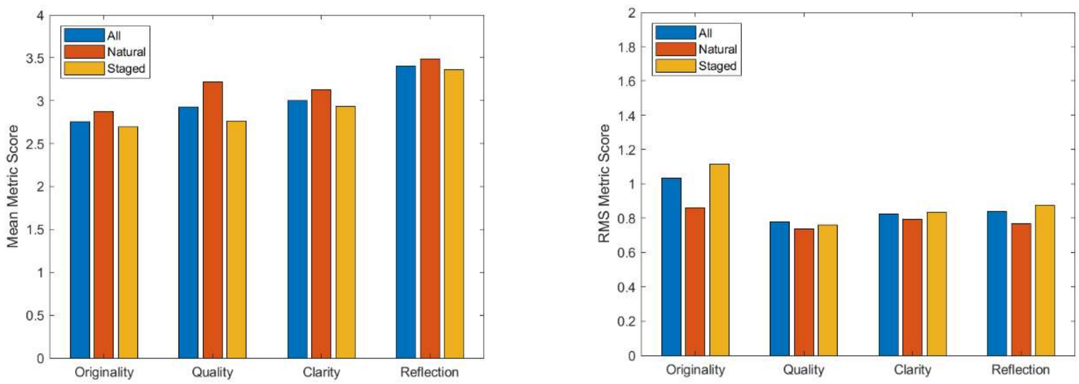

Figure 6: Average and RMS Metric Scores

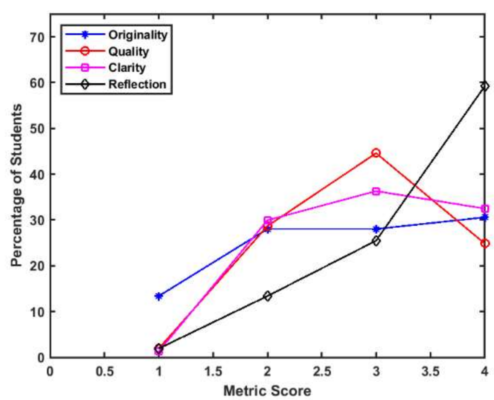

Figure 7: Metric Student Distribution

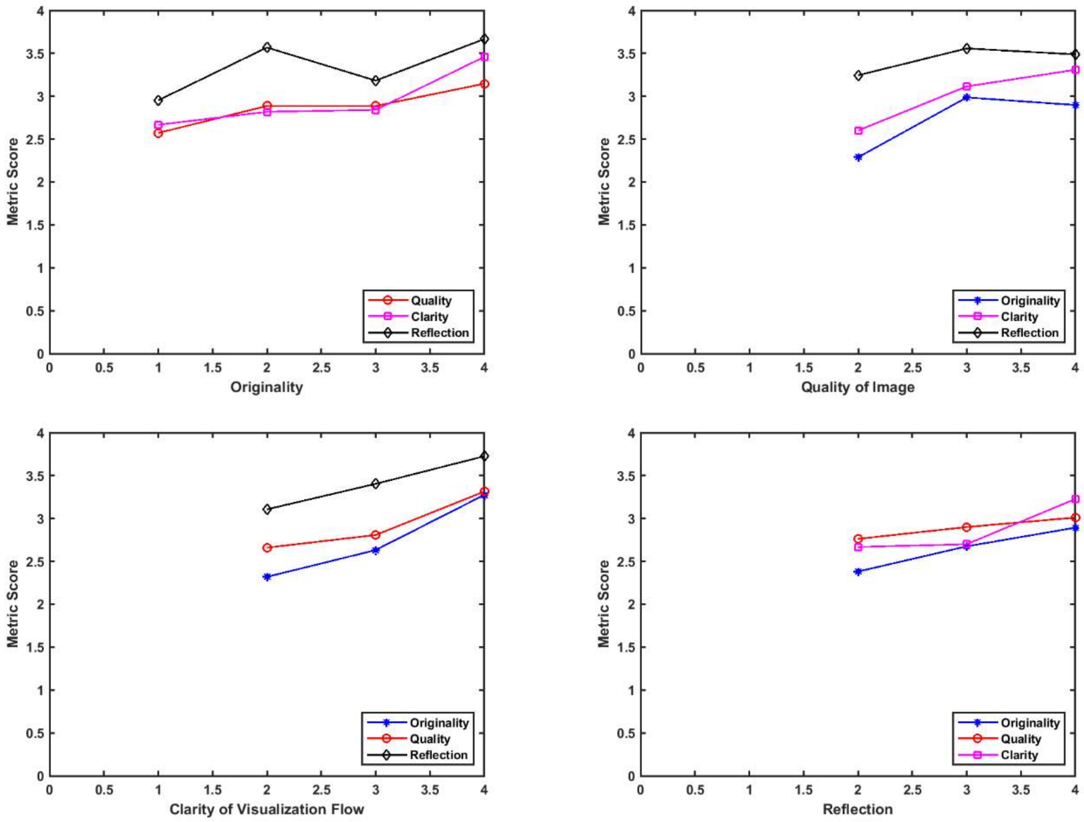

Figure 8: Metric Sorted Average Metric Scores

The mean sorted data are shown in Figure 8 to show relationships between metrics. Note that the data for metric scores of 1 were eliminated for all cases except originality due to the low number of students in those bins which made the mean statistically unreliable. The data show a general trend of an increasing relationship between the metrics. For example, students that scored low in originality generally also scored low on quality, clarity, and reflection. This was observed most strongly when the data were compared based on the clarity metric. This result indicated that the students who were most successful at staging a subject in which the flow was successfully visualized were most likely to score well in all metric categories. Finally, metric scores were considered with respect to student's final numeric grade for the course, Figure 9. This relationship was investigated to determine how well the project was able to reach students, particularly those with low course performance. Students were sorted in to bins of 100-90, 90-80, 80-70, 70-60 and <60. Means scores for each of the metric values were then calculated for each bin. The bin data for students with a course grade <60 were omitted again due to low number of students in this bin (4/157). These data indicate an increasing relationship in each metric value with the course grade. It was clear that students who were performing well in the class were the most likely to develop original ideas, execute the imaging well (both in terms of photographic quality and ability to see the flow), and had the most in depth reflections. This was not surprising given that students who were performing well in the course were mostly likely also highly engaged in the course. It was at first somewhat disappointing that the reflection metric tracked with course grade as well. It had been hoped that the student engagement and performance in the project would be more uniform. However, the scores on the reflection metric were always significantly above the other metric scores and ranged between 3 and 4, even for the students with lower course grades. This indicated that the students were able to find a subject for the project that was interesting to them, which met the goal of the project.

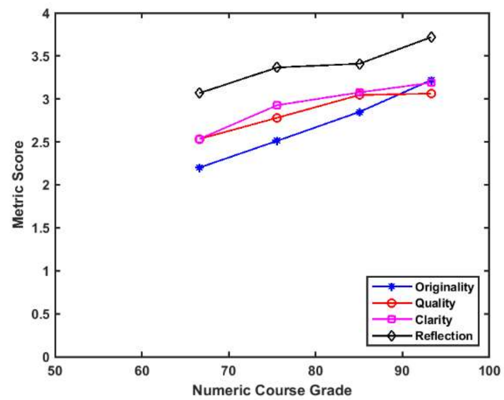

Figure 9: Mean Metric Scores versus Course Grade

Conclusions

This paper details a flow visualization project in an introductory undergraduate fluid mechanics course. The project asked the students to find a fluid dynamic flow field that they found personally interesting and could see a fluid phenomenon, and then take a picture of it. Students were asked to reflect on the image and communicate why they found the image to be interesting to them. The definition of "interesting" was left open to the students interpretation. The goal of the project was for students to connect the broader subject of fluid mechanics with their own personal interests to better engage them in the material. Project outcomes were assessed by assigning scores in four metric categories: Originality of project subject, aesthetic Quality of the image, Clarity of the flow visualization, and seriousness of the Reflection. The metrics were not used to assign the project grade. Metric scores were then correlated with each other and with the final course grade to assess the success of the project to meet the goal.

Students presented a broad variety of flow fields that included both natural (33%) and staged subjects (66%). The large number of staged projects indicated that the students were actively choosing flow fields to image. The projects that used natural settings tended to be motivated by personal experiences or interests. Both of these indicated that students were actively engaged in the project. Originality of the project subject was a weak indicator of project success. Some projects that score low for Originality were chosen because they were "easy". For example, many projects used a magnetic stirring rod to generate a vortex in a beaker. Students had easy access to this device as it was being used in another class near the project due date. Other project subjects (e.g. flow in streams or waterfalls) scored low in Originality because they were historically popular with students. However, these projects tend to be chosen because of a student's personal connection with the picture and therefore other metrics like Reflection scored high. Many students chose highly original subjects that were not discussed or shown as an example in class. These projects, unsurprisingly, scored high in all metrics. Similarly many students chose subjects for the project that were highly personal. Again, these projects typically presented high quality images and reflections due to the personal connection with the subject.

The metric scores gave insight into the success of the project to achieve the goal of connecting the broader topic of fluid mechanics with the student's personal lives. The metrics that directly indicate effort (i.e. quality, clarity, and reflection) all had mean values above 2.5/4. This result showed that the students were engaged in the project. In particular the metric scores on reflection were always 0.5 points higher than the other metric scores. This showed that students were engaged in the project sufficiently that they were able to pick a flow field that was personally interesting and communicate that. This was true even for students who has lower final course grades. Overall the project appeared to be successful in meeting its goal of having students connect the course subject to their personal lives.

Going forward several changes to the project will be made. First, the project description will be changed to better describe the requirements for the reflection section of the written report. The expectations for the scope of the reflection were not well described, and it is felt that the quality of the Reflections can be improved by clarifying the expectations. Second, the students will be asked to more clearly describe the flow phenomenon they are imaging. Currently the students are being asked to describe the image and many projects lacked a clear description of what is being shown (separation, sheet break-up into drops, etc.). This will enable a better assessment of the clarity metric and allow for the addition of a description metric. Finally two additional assessment tools will be added. Other faculty will be asked to look at the projects and provide assessment scores. This will make those assessment scores less subjective by adding additional independent observations. Students will also be given a survey to assess their level of engagement and ability to see the relevance of "fluid mechanics" in their personal and professional lives. This will be done at the beginning and end of the semester to quantify changes in attitudes.