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Teaching Fluid Mechanics through Photography

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Abstract
As part of the General Education (GenEd) program at the Pennsylvania State University, we offer an experimental course on flow visualization to undergraduate students. This course aims to bridge the gap between two distinct areas of knowledge: the art and science of fluid mechanics. Designed for students with minimal to no background in photography or physics, this non-mathematical course provides an opportunity for students to explore a variety of aesthetic issues through practical and creative assignments. The course consists of lectures on photography skills, fluid physics, visualization techniques, critique sessions, and a guest lecture. Assignments consist of images paired with written technical reports, and critique sessions. The primary objective of the course is "integrative thinking". Other course objectives evaluated through students' assignments and projects are "creative thinking" and "effective communication". Some samples of student work are presented, and the outcomes are discussed. This course proved to be very successful in attracting all students (male and female) in both engineering and non-engineering majors.

Introduction
In recent years, there has been a growing interest in bridging the gap between science and art. Several organizations have emerged with the aim of promoting the integration of art and science, including Art & Science Collaborations, Inc. (ASCI), International Society of the Arts, Mathematics, and Architecture (ISAMA), and International Society for the Arts, Sciences, and Technology (ISAST). Academia has also seen an increase in efforts to engage students in course materials through innovative teaching methods. One such effort in fluid mechanics is a course on the physics and art of flow visualization, developed by Dr. Jean Hertzberg at the University of Colorado, Boulder [1-3]. This technical elective, offered to engineering students and as studio credit to fine arts students since 2003, has proven to be highly effective.

Distinguished Professor Emeritus Gary Settles, from the Pennsylvania State University, is a self-taught painter whose works center on the subject of fluid dynamics. He encourages others to explore the integration of fluid dynamics and art [4,5]. At the University of the Pacific, Professor Said Shakerin has utilized water fountains with special effects as a medium to inspire his students to incorporate fluid dynamics into their artistic projects [6-8]. These water fountains, made possible by advances in computer control technology, have become popular in the last 25 years in theme parks, resorts, and city centers. The integration of science and art presents a unique opportunity to encourage creativity and innovation. By promoting collaboration between disciplines, we can inspire new perspectives and foster a deeper understanding of the world around us.

In contrast to efforts promoting the integration of art and science, ABET currently precludes engineering students from applying any fine art studio courses towards their degree, except as GenEd courses. This restriction can send the message that artistic creativity is not valued in engineering, which is not the case in engineering design. This may discourage creative students from pursuing engineering, resulting in reduced intellectual diversity in students and possibly reduced gender and cultural diversity as well. However, many universities now recognize the importance of a comprehensive education that includes interdisciplinary studies. This has led to a new movement to turn STEM (science, technology, engineering, and math) into STEAM, with the A representing Art [9]. The authors wish to showcase their work in the national STEM to STEAM dialogue as an example of how this movement can successfully unite art and science. The first showcase will be at the American Physical Society, Division of Fluid Dynamics (APS-DFD), as an education symposium lecture. Additionally, the plan is to present this work as a workshop at Lilly Conferences, which provides opportunities for the presentation of scholarship of teaching and learning. With more historical background, this work could showcase the development within fluid mechanics against the backdrop of scientific progress.

In April 2015, the University Faculty Senate at the Pennsylvania State University approved a new requirement for Integrative Studies within the General Education program. The implementation details for this requirement were approved in March 2016 and apply to students who started at the Pennsylvania State University during or after the summer of 2018. The Integrative Studies requirement offers two pathways for students to fulfill it: either by completing 6 credits of inter-domain or linked coursework. Inter-domain courses are 3-credit courses that combine two General Education domains (Natural Sciences (GN), Health and Wellness (GHW), Arts (GA), Humanities (GH), Social and Behavioral Sciences (GS)) within a single course. These courses cover both domains with approximately equal attention, incorporating course topics, assignments, or other course components. Linked courses, on the other hand, consist of at least two courses (totaling at least 6 credits) and represent two different domains, creating a functional "linkage" for students. Each linked course must have a purposefully integrated component across all the courses in the "linked set." Such courses have never before been required or had a recognized designation at the Pennsylvania State University, and therefore the University has taken measures to make these types of courses available to students.

To promote the development of courses that meet the criteria for Integrative Studies, the Office for General Education at the Pennsylvania State University invited seed grant proposals. The General Education seed grants were awarded to projects that proposed courses that are expected to have broad student appeal, align with the goals of the General Education update, and reflect other General Education learning objectives, with priority given to proposals that were transferable to a range of university campuses and that engage faculty from different colleges or units. The Flow Visualization course was a natural fit for this initiative and received the seed grant award to develop the integrated-domain course on the art and science of fluid motion over the academic year of 2016-2017. The course was inspired by Dr. Jean Hertzberg's successful course at the University of Colorado, Boulder [10] and aimed to explore the importance of creative aesthetics and making art in the education of engineers and scientists. The course recognized the significant contribution of images to the development, communication, and popularization of science and engineering, and emphasized the importance of developing good observational skills for both engineers and artists. Other examples of integrative courses developed through the seed grant initiative include Politics of Hip Hop, From Beast Books to Dinosaurs Resurrected, Race in the Humanities and in the Social Sciences, Psychology in the Cinema and the Arts, and Scientific Controversies and Public Debate. These courses represent innovative approaches to teaching and learning that integrate multiple disciplines, promote critical thinking, and engage students in active learning.

The course development process culminated in the creation of a comprehensive set of materials that included a detailed syllabus outlining course objectives, weekly assignments, assessments, and a reading list, as well as a range of course materials and resources. Additionally, the materials featured sample evaluation criteria that enabled the assessment of integrative thinking and other General Education objectives addressed in the course. Following the completion of the course materials, a curricular course proposal was submitted to UFS and underwent consultation procedures. Ultimately, the proposal was approved by UFS in April 2018 and the course was offered to students for the first time in the fall of the same year.

Throughout the course, students had access to a variety of fluid apparatus and were encouraged to experiment with creating novel flows. Each image produced by the students was required to be accompanied by a write-up, which some of the art students found surprising. The student work was then evaluated for both artistic and scientific merit, with an emphasis on developing an appreciation for the beauty of fluid physics that surrounds us in our daily lives. Despite being a radical departure from typical engineering curricula, the course was very successful in attracting a diverse group of graduate and undergraduate students, particularly women studying engineering. One of the key outcomes of the course was the recognition by students of the aesthetic value of fluid physics and the motivation it provided for life-long learning.

Course Objectives and Description

This course offers a unique blend of scientific and artistic techniques for visualizing fluid flows in the laboratory and in everyday life. Through hands-on exploration, students learn to use dyes and particles to create visual representations of the physics of fluid flow. They also gain technical expertise in photographic techniques, such as capturing atmospheric clouds. Assignments are designed to be student-driven, encouraging both individuals and mixed teams of undergraduate students from diverse majors to create images using their own techniques, and to document their work in written reports. The course also addresses philosophical questions such as "What makes an image scientific?" and "What makes an image art?" to encourage students to reflect on the intersection of science and art. The consensus was that an image of fluid flow can be considered scientific if the conditions of the fluid flow and image production are known, while the interpretation of whether an image is art is subjective.

Despite the course's focus on science, images produced by students are unarguably artistic and visually captivating. This course requires no prior experience in Mathematics or Physics and is taught at a level accessible to students of all majors with a High School knowledge level. Through this course, students gain a deeper appreciation of the beauty of fluid physics and the motivation for lifelong learning.

The main objectives of this course are:

- Integrative Thinking – The primary objective of this course is to promote Integrative Thinking among students. By exploring the visualization techniques for fluid flows from both scientific and aesthetic perspectives, students learn to look at things from a different angle and appreciate the interdisciplinary nature of science and art. Through assignments and activities, students develop the ability to synthesize knowledge across different domains and transfer it to other contexts. The course cultivates a unique set of analytical and creative skills that help students to cultivate the relationship between science and art, regardless of whether they continue to pursue the study of fluids or photography in the future. Overall, the course aims to foster life-long learning and encourage students to become more open to diverse fields of science and engineering.

- Creative Thinking – This course provides an opportunity to foster creative thinking by cultivating an appreciation for the beauty of fluid physics that surrounds us every day. Fluid physics is responsible for a range of natural phenomena, from stunning landscapes to devastating disasters such as floods, tornadoes, and wildfires. By exploring the relationship between art and science, students can gain a deeper understanding of how the two fields intersect and influence one another. For instance, they can learn how images and videos of natural disasters are both scientifically informative and aesthetically captivating. In addition to scientific goals, many fluid physicists are also driven by a fascination with their subject, which underscores the potential for lifelong learning and engagement in the field.

- Effective Communication – Another important objective of this course is to teach students the importance of effective communication in scientific and artistic fields. Students learn that the physics of fluids cannot be conveyed solely through verbal means, but also through visual communication. Through their coursework, they are challenged to find the beauty in the interaction between different fluids and to document their findings through photography. Additionally, students learn how to present their final projects in the form of a poster and communicate their ideas effectively to a broad range of audiences, including those outside their field of study. This combination of visual and verbal communication skills will serve them well in their future endeavors, regardless of their chosen field.

To participate in the course, students were required to bring their own cameras that had the ability to manually focus and control exposure settings, such as shutter speed, aperture, and ISO. The photography professor provided recommendations to assist students in selecting appropriate cameras. Additionally, through a seed grant, five Nikon D3400 DSLR Cameras with AF-P DX NIKKOR 18-55mm F/3.5-5.6G VR Lens were purchased for students to borrow from the library on a first-come, first-served basis. Adobe Photoshop and Bridge were recommended for downloading and editing images, and all students had access to them for free. Engineering students were advised to use the "Flow Visualization: Techniques and Examples" book by A. J. Smits and T. T. Lim as a reference textbook. [11]

Course Structure

We co-teach the Flow Visualization course to a diverse group of 24 undergraduate students every semester. The students are from various majors including engineering, psychology, art, science, business, and communication. The course is designed to meet General Education requirements in Art (GA), Natural Science (GN), or Integrative Studies (GI) domains based on students' preferences. The class meets twice a week, on Tuesdays and Thursdays, for 75 minutes each session.

At the start of the semester, the course covered two lectures on fluid properties, including topics such as density, viscosity, temperature, pressure, buoyancy, and more. Additionally, two lectures were dedicated to teaching basic photographic techniques, such as Shutter Speed, Aperture, ISO, and White Balance. These lectures were primarily for the benefit of students who had little to no experience in science or photography. The course emphasized the quantitative aspects of optics and the interrelationship of spatial and temporal resolution in the measurement of fluid flows. The course was structured around six major topics, with each topic consisting of a set of four classes. The first class in each set featured a lecture on the scientific principles and visualization techniques of the topic. The course was designed with a focus on making the lectures accessible to students from diverse academic backgrounds, thus, lectures were delivered using visual aids, educational videos, and quizzes to reinforce the material covered. The second class was a photography session where students put into practice the techniques discussed in the lecture.

Usually, students participated in group photography sessions either in a lab or outdoors, with actual image acquisition assigned as homework. The third class was an edit/submit session where students edited their images using Photoshop and wrote a report documenting their process. Students were taught how to use appropriate tools in Photoshop to edit their top images in preparation for their reports. Finally, the fourth class was a critique session where students presented their work and received feedback from their peers and instructors. Each topic was concluded with remarks and an introduction to the next topic, and students were assigned scientific articles to read to deepen their understanding of the topic. The six selected topics were:

1. dye flow visualization in milk & dye mixture (Fig. 1),
2. clouds, humidity, dews, and weather prediction (Fig. 2),
3. florescent dye visualization in dark and vortex flows (Fig. 3),
4. particle imaging and smoke visualization (Fig. 4),
5. surface waves (Fig. 5),
6. heat convection and kitchen flow (Fig. 6).

Fig. 1. Assignment 1- milk & dye mixture

Fig. 2. Assignment 2- clouds, humidity, dews

Fig. 3. Assignment 3- florescent dye visualization in dark

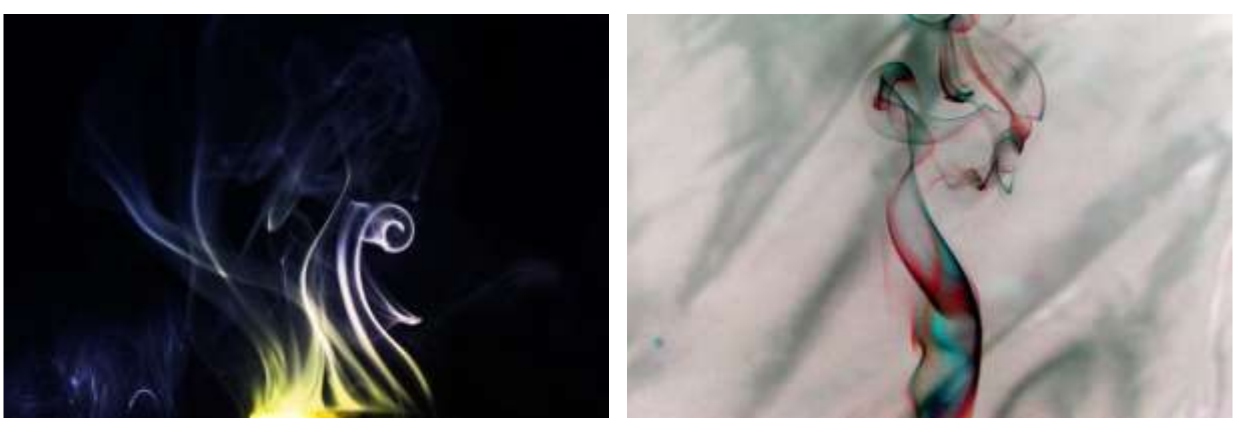

Fig. 4. Assignment 4- smoke visualization

Fig. 5. Assignment 5- surface waves

Fig. 6. Assignment 6- heat convection and kitchen flow

In addition to the final project, the course included 6 bi-weekly assignments, 2 quizzes, and several in-class activities to encourage active participation from students. The assignments were graded based on the quality of the images, the scientific statements, and the effectiveness of the visualization techniques. Participation in critiques, using rubrics as a guideline, was also an important factor in determining the grade for each assignment. The instructor and peers provided qualitative feedback during the critique sessions to help students improve their work.

Assessing Integrative Thinking

The GenEd Integrative thinking objective we assessed, is defined by Penn State as the ability to synthesize knowledge across multiple domains, modes of inquiry, historical periods, and perspectives, as well as the ability to identify linkages between existing knowledge and new information. Individuals who engage in integrative thinking are able to transfer knowledge within and beyond their current contexts. We collected two things to assess the above objectives broadly for the University:

1. Student scores on the element(s) of the assignment aligned with integrative thinking (scored using the rubric developed in collaboration with faculty teaching integrative thinking courses provided in Appendix A).
2. Students' perceptions of their own integrative thinking skills collected via a survey administered by OPA later in the semester.

The results are provided in the next section.

Course Outcomes

One notable outcome of the course was the students' commitment to using environmentally friendly materials. They used materials, such as food coloring, non-toxic stage fog, fluorescent detergents and highlighter ink, and pearlescent shampoo. By doing so, they not only found effective substitutes for commercial rheoscopic fluids but also contributed to reducing the environmental impact of their experiments. Furthermore, several of the flows examined necessitated only basic photographic equipment and minimal fluid flow apparatus.

Another notable outcome of the course was the unexpected popularity, particularly among female students. Despite being a science course, the class had a high enrollment of female students, with 40% of the class population. The popularity of the course is evident from the substantial waitlist of students trying to enroll, which suggests a growing interest in flow visualization and its artistic applications. This suggests a promising new approach to increase the participation of women in Mechanical Engineering (ME) or Aerospace Engineering by addressing the traditional perception of the discipline. Mechanical Engineering is often viewed as a dry and overly utilitarian field, focused on solid mechanics such as gears and levers, which may deter women from pursuing it. As a result, the enrollment of women in engineering has remained low nationwide, at less than 14% of the undergraduate student population over the past 10 years, with slow growth. This small percentage results in a low fraction of women engineers in the workforce, at approximately 6.5%. In fluid flow research, the female membership of the American Physical Society – Division of Fluid Dynamics (APS-DFD) is approximately 7%, slightly lower than the overall APS membership at 10%. However, the popularity of this course among women suggests that promoting its creative aesthetics, combined with hands-on and team-oriented techniques, may be an effective way to attract more women to the field. By highlighting the novel aspects of the course, this approach could help break down the barriers that have traditionally deterred women from pursuing mechanical engineering and increase diversity in the field.

During the final project poster presentation, students were asked to demonstrate their effective communication skills. The result was remarkable, with 95% of students reporting that it significantly helped them initiate conversations and engage with the audience. Additionally, 63% of students found it useful in handling Q&A sessions, and 74% of them reported increased confidence in their communication skills. Some students (26%) also mentioned that they learned how to create a poster and organize their poster layout. When asked for suggestions to improve the course, one main recommendation from students was to introduce short quizzes after each topic to reinforce lecture content.

The survey results indicate that students found the course engaging and appreciated the combination of science and photography. However, some students provided suggestions for improvement. In response to the question, "What do you like about the course?", most students mentioned the opportunity to explore their creativity and view things from a new perspective. When asked about meeting the course expectations for "Integrative Thinking" learning objectives in both Arts and Natural Sciences domains, all students reported feeling confident that they were meeting these expectations. Each semester, students who have already taken Fluid Mechanics reported how this course helped them effectively cover the physics of fluid flow by using Flow Visualization as a powerful tool. The course was carefully designed to avoid overlap with other engineering courses. For students unfamiliar with fluids, the course provided a new perspective, while those who already had some knowledge of fluid mechanics found the course even more enlightening. This indicates that cross-disciplinary coursework like this course is an effective method of education that can benefit people at all levels.

Conclusions

While the impact of this course may be limited, it represents a departure from traditional science and engineering curricula and could serve as a model for future courses that integrate art and science. The Flow Visualization class showed significantly more positive attitude shifts than regular science and art classes. Another outcome of this experimental course indicates that students from diverse backgrounds can successfully perform Flow Visualization. Notably, there were no significant variations in the scientific or artistic quality of their images or any observable patterns that correlated their work to their majors. The course demonstrated that with proper training, anyone can create stunning images and accurately document interesting fluid phenomena. It is noteworthy that many students had no prior experience with the flows they generated or photography. The feedback from the students highlights the transformative impact of the course on their perception and motivation towards learning. Students' comments indicate that the course has a positive impact on their life-long learning and personal growth, as a change in perception is the first step towards understanding. To further evaluate the effectiveness of the course in promoting life-long learning, additional assessments will be conducted in future course offerings. In the future, the course will be further evaluated to determine whether it enhances students' visual expertise. Additionally, a new survey will be developed to investigate students' perceptions of the aesthetic and utilitarian aspects of their work. By identifying the specific factors that contribute to students' positive attitudes towards the Flow Visualization course, it may be possible to incorporate those elements into other engineering classes to improve learning outcomes and increase student engagement.

Acknowledgement

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Appendix A: Integrative Thinking Rubric

This rubric was used to score students on a significant assignment related to integrative thinking. **The rubric enables consistent scoring of students across multiple courses regardless of the type of assignment or how each instructor grades.** These scores were not included in students' grades.

Criterion	**Developing (1)**	**Satisfactory (2)**	**Exemplary (3)**
Synthesizes knowledge across multiple domains, modes of inquiry, historical periods, or disciplinary perspectives.	Knowledge, skills, abilities, theories, or methodologies from multiple disciplines are combined or applied **in a rudimentary, mechanistic way and/or integrated through superficial criteria.** Response may include: concepts and theories presented as matter of fact; no evidence that purpose of multi-disciplinary approach was considered; misconceptions are evident.*	Knowledge, skills, abilities, theories, or methodologies from multiple disciplines are combined or applied **adequately with appropriate emphasis.** Response may include: use of metaphor, conceptual framework, causal explanations or other devices provides evidence of growing understanding; purpose of multi-disciplinary approach present, but not completely addressed; and/or no major misconceptions are evident.*	Knowledge, skills, abilities, theories, or methodologies from multiple disciplines are combined or applied and **balanced coherently, elegantly and creatively, resulting in a hybrid form or new insight.** Response may include: use of metaphor, conceptual framework, causal explanations, or other devices demonstrates a clear and mature understanding; purpose for multi-disciplinary approach is fully articulated; and/or no misconceptions are evident.*
Identifies connections between existing knowledge and new information.	Connections between students' prior knowledge and new information are present, but not articulated clearly or thoroughly.	Connections between students' prior knowledge and new information are clearly and thoroughly articulated.	Connections between students' prior knowledge and new information are complex, integrated, and articulated clearly and thoroughly.

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