

THE TRANSFORMATIVE EXPERIENCE IN ENGINEERING EDUCATION

By

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Abstract

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The Transformative Experience in Engineering Education

Thesis directed by Professor John K. Bennett and Associate Professor Jean R. Hertzberg

This research evaluates the usefulness of transformative experience (TE) in engineering education. With TE, students 1) apply ideas from coursework to everyday experiences without prompting (*motivated use*); 2) see everyday situations through the lens of course content (*expanded perception*); and 3) value course content in new ways because it enriches everyday affective experience (*affective value*). In a three-part study, we examine how engineering educators can promote student progress toward TE and reliably measure that progress.

For the first study, we select a mechanical engineering technical elective, Flow Visualization, that had evidence of promoting *expanded perception* of fluid physics. Through student surveys and interviews, we compare this elective to the required Fluid Mechanics course. We found student interest in fluids fell into four categories: complexity, application, ubiquity, and aesthetics. Fluid Mechanics promotes interest from application, while Flow Visualization promotes interest based in ubiquity and aesthetics. Coding for *expanded perception*, we found it associated with students' engineering identity, rather than a specific course. In our second study, we replicate atypical teaching methods from Flow Visualization in a new design course: Aesthetics of Design. Coding of surveys and interviews reveals that open-ended assignments and supportive teams lead to increased ownership of projects, which fuels risk-taking, and produces increased confidence as an engineer.

The third study seeks to establish parallels between *expanded perception* and measurable perceptual expertise. Our visual expertise experiment uses fluid flow images with both novices and experts (students

who had passed fluid mechanics). After training, subjects sort images into laminar and turbulent categories. The results demonstrate that novices learned to sort the flow stimuli in ways similar to subjects in prior perceptual expertise studies. In contrast, the experts' significantly better results suggest they are accessing conceptual fluids knowledge to perform this new, visual task. The ability to map concepts onto visual information is likely a necessary step toward expanded perception.

Our findings suggest that open-ended aesthetic experiences with engineering content unexpectedly support engineering identity development, and that visual tasks could be developed to measure conceptual understanding, promoting expanded perception. Overall, we find TE a productive theoretical framework for engineering education research.

Dedication

To my parents, Pete and Ruth Dueringer, my first teachers in so many ways.

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Chapter 1 – Introduction

This research evaluates the role and benefit of transformative experience (TE) in engineering education. Transformative experiences lead students to 1) apply ideas from coursework to everyday experiences without prompting (also called *motivated use*); 2) see everyday objects or situations through the lens of course content (*expanded perception*); and 3) value course content in new ways because it enriches everyday affective experience (*affective value*) (Pugh, 2011).

The notion of a transformative experience stems from John Dewey's seminal theory of experiential learning and is influenced by his work on the value of aesthetic experiences (Dewey, 1934, 1938; Pugh & Girod, 2007). Simply put, students' perception of the world should change as a result of new knowledge and abilities. They should naturally relate course concepts to what they see in the larger world, put those concepts to work, and significantly, enjoy the experience.

We employ both qualitative and quantitative methods to build connections between demonstrable examples of TE, teaching methods that influence TE, and measurable tasks in the realm of perception, which may give rise to effective assessments related to TE. As explored in Chapter 2, current engineering educators are exploring ways to retain more students, which in turn requires an understanding of what motivates and engages students. An evaluation of transformative experience allows us to go beyond traditional assessments like exams and homework sets to ask whether students developed an understanding of the material sufficient for application in non-academic settings. Can the graduate actually use what she has learned? This helps us frame our primary research question:

How can educators promote student progress toward a transformative experience, and reliably measure progress toward that goal?

This larger question is addressed through three lines of inquiry:

1. **Student Affect:** In the context of a specific engineering domain, what is the relationship between student affect and a concurrent expansion of perception?

2. **Teaching Methods:** What teaching methods and learning activities contribute to a transformative experience for students learning engineering?
3. **Perception:** What is the link between perceptual expertise and the transformative experience? How can we measure perceptual expertise in a particular engineering domain, such as fluid dynamics?

In Chapter 3, we summarize the learning theories that form the foundation of our approach to this research, as well as relevant work from psychology, highlighting studies of perception, motivation, creativity, and perseverance. The chapter concludes by summing up why the transformative experience acts as an effective lens for bringing together what may appear to be unrelated aspects of education.

For the first and second lines of inquiry, Chapter 4 provides detailed descriptions of the three courses we investigated. Chapter 5 explains the choice of methodology and data collection and outlines our methods. We employed surveys, with both closed and open response items, as well as interviews, in pre- and post-course pairs. Chapter 6 examines what was revealed about relationships between the three indicators of TE as related to their associated course contexts.

For the third line of inquiry listed above, Chapter 7 states both the experimental methods and the resultant findings. These methods are borrowed from our psychology colleagues, who have tested for perceptual expertise using stimuli such as cars, faces, and birds. We share the results of our visual expertise experiments, and summarize the work on this third line of inquiry.

As disparate as these multiple lines may seem, in Chapter 8 we show how they each contribute to the process of understanding the role of the transformative experience in engineering education. This chapter also details our contributions to engineering education research, describes the limitations of this work, and proposes future avenues of inquiry.

Chapter 2 – Problem Statement

This chapter addresses the need for alternative approaches to engineering education. We describe previous approaches to improving engineering education and the gaps in those efforts. We address the specific motivations that lead to our use of the transformative experience (TE) as a theoretical lens, and discuss why we initiated our study of Flow Visualization in particular. This chapter concludes with a formal statement of our research questions.

The Two Part Problem

Broadly stated, the problem I seek to address is this: students often cannot or do not apply what they learned while earning engineering degrees in engineering workplaces (Landivar, 2013). Perhaps students do not see how their courses connect with real situations they encounter in the workplace. Perhaps they do see the connections, but they do not want to use what they learned, professionally. Which part of this is the true problem? Or is it a messy combination of both?

Beyond school, students quickly discover their theoretical knowledge, or even their ability to apply that knowledge, is less important than what they are willing do with that knowledge. Even when students can make the necessary connections, some find they are uninterested in doing so (X. Chen, 2013; Landivar, 2013; US Census Bureau, 2014). It is difficult, at times, to tell the difference between the students who cannot use in the real world the skills they have gained in school and those who can, but choose not to.

This two-part problem is expressed in a number of interesting findings. For example, there has been a push for institutions of higher education to produce greater numbers of qualified engineers, and more broadly, qualified professionals in all of the STEM (science, technology, engineering, mathematics) disciplines (My College Options & STEMconnector, 2012; National Science Board, 2010)¹. This effort is

¹ There are dissenters to this argument, such as Teitelbaum, who claim we are creating a boom-and-bust cycle of STEM professionals, and there is no pointed need to significantly increase the number of

fueled by the industry view that engineers are innovators and that as a result, their work fuels economic growth. In fact, one study called innovation the “integrative, meta-attribute” employers expect of all engineering graduates (Radcliffe, 2005). In addition, there are calls to create “an increasingly diverse talent pool” (National Academy of Engineering, 2004, p. 4), and evidence that more diverse groups of employees are, in fact, more innovative (Page, 2007).

One challenge universities face in meeting that demand is high rates of attrition among engineering majors. Many studies document the “leaky pipeline,” and strive to understand the reasons students, leave STEM programs during their undergraduate years (X. Chen, 2013; Imbrie, Lin, & Reid, 2010; D. W. Knight, Carlson, & Sullivan, 2007; Moller-Wong & Eide, 1997; Seymour & Hewitt, 1997). These attrition studies frequently reveal that women and under-represented minorities leave in numbers disproportionate to their presence in the programs (Blickenstaff, 2005; Seymour & Hewitt, 1997). One answer might be that those who leave STEM degree programs are incapable or unprepared², but the data do not support this as the sole cause. While many students do leave because of lower academic performance, many do not (X. Chen, 2013). One study discovered that women who leave STEM programs have the same GPAs as women who stay (Blickenstaff, 2005), and another found that women who leave have *higher* GPAs than the men who remain (Seymour & Hewitt, 1997). These findings suggest that more is going on than simply “weeding out” the students who “don’t have what it takes to become engineers.” We should also acknowledge that education is a formative process during which we make discoveries about what we can do and what we want to do. Of course some students will leave their STEM majors. When students leave, we want it to be because they have located a more authentic passion, not because they are fleeing poor teaching and a combative environment.

engineering graduates at the current time (2014). Even if this argument proves to be true, improving the efficacy of engineering education will create a steady supply of motivated and well-trained engineers, a goal Teitelbaum supports.

² There is a distinct difference between incapable and unprepared, as the GoldShirt program as CU has demonstrated, where students from underrepresented groups are often successful after a “performance-enhancing” year (Ennis et al., 2010).

Unfortunately, students are leaving for those reasons. We know this through studies such as the seminal “Talking about Leaving” (Seymour & Hewitt, 1997), which documented attrition rates for science, math, and engineering majors across seven four-year institutions of higher education and reported its findings in chapters with names including “The Weed-Out Process” and “The Unsupportive Culture.” Since that time, various other studies have documented similar struggles of students who choose to leave STEM majors (X. Chen, 2013; Chesler, Barabino, Bhatia, & Richards-Kortum, 2010; Thompson et al., 2007). Whether we work to correct this through improved pedagogy or shifts in cultural climate, or both, raising retention rates within our programs would obviously create more engineering graduates.

Yet, is degree completion our only concern? The majority of STEM-degree holders do not work in a STEM field, according to the US Census Bureau (2014). Many students leave engineering and other STEM disciplines as they enter the workforce (Lowell, Salzman, Bernstein, & Henderson, 2009; National Science Board, 2010). In addition, there is evidence that the highest-achieving students in U.S. engineering programs do not go on to work in engineering (Lowell et al., 2009). While poor economic circumstances may have made finding a job a challenge for many recent graduates, surely top students had a choice in their professions. If we are asking “why don’t more students complete engineering degrees?” we only address part of the problem. The question should be “why don’t we have more engineers entering the workforce?”

So, it is not enough to track student progress within a degree program or to target higher rates of degree completion. We need to understand more about why some students persist in using the skills and knowledge they develop while earning their degrees and others do not. We need to understand what motivates (or demotivates) them to use their engineering skills beyond the classroom.

Approaches to Answer the “Can they?” Question

Much of engineering education research targets individual engineering courses, and is focused on refining content, developing assessment tools, or creating more interactive classrooms (Fraser, Pillay,

Tjatindi, & Case, 2007; Prince, Vigeant, & Nottis, 2012; Stern et al., 2006). These types of studies ask questions such as “are we teaching the right content?”, “do our assessments actually measure whether students learn it?”, and “does a particular change improve student outcomes on the assessments we developed?” These are important questions, worth answering.

Once we address whether students are learning what we want them to learn, the next question becomes, can they transfer that knowledge and skill from the classroom to the workplace? This question is sometimes called the “transfer problem” (Pea, 1987), but it also appears under other names including “awareness” (Rodd, 2010), or the “need to activate resources” (Hammer, Elby, Scherr, & Redish, 2005). Educators who are aware of the situated nature of learning can intentionally develop learning environments that provide appropriate scaffolding for students (J. S. Brown, Collins, & Duguid, 1989). However, without this awareness, the contextual backdrop can become a veneer, inhibiting students from seeing how their new knowledge or skills can be applied in other contexts, what Engeström calls encapsulation (1991). As a result, engineering students who learn only through structured problem sets may not know how to apply that knowledge once in the workplace (Lattuca, Terenzini, Volkwein, & Peterson, George, 2006).

In response to these findings, there has been an increasing emphasis on design courses and capstone courses, which aim to have students integrate their skills in a single long term project. Such courses provide the opportunity to develop and measure a number of professional skills, including communication and teamwork (Gilbuena, Sherrett, Gummer, Audrey, & Koretsky, 2015; Lattuca et al., 2006). These abilities are often called “soft skills” although some engineering educators would rather they be called “the missing basics”, because they are essential for students to become successful engineers (Goldberg & Somerville, 2014).

One team has developed measures for how well students can demonstrate *contextual competence* (Ro, Merson, Lattuca, & Terenzini, 2015), defined as “an engineer’s ability to anticipate and understand the

constraints and impacts of social, cultural, environmental, political, and other contexts on engineering solutions” (Ro, Lattuca, Merson, State, & Terenzini, 2012). This work goes beyond simple notions about transferring learning from one context to the next, and defines the broader arena in which engineers work. The focus on whether students have the ability to be successful in the engineering workplace represents only one half of the two-part problem. The unanswered question is whether they want to (Lowell et al., 2009).

Approaches to Answer the “Will they?” Question

It is only recently, and somewhat reluctantly, that engineering educators have openly addressed motivation and other emotionally-charged constructs as important components in what we do. In a 2015 editorial about efforts to improve engineering education through the creation of Olin College in Massachusetts and the iFoundry at the University of Illinois, Goldberg and Somerville noted that “all the relevant change variables are emotional.” Perhaps more importantly, they confessed that “this was excruciatingly hard for a couple of engineers to understand and embrace, but once we did, we knew there was no going back” (2015, p. 4). This acknowledgement of students’ emotional experiences changes the direction for reform efforts from the narrow scope of pedagogy and curricular support to a broader conversation that includes student engagement and the development of a supportive community. Efforts to understand student self-efficacy have included studies of identity, or whether students think of themselves as engineers (Johri & Olds, 2011; D. Knight, 2013), and defining what is meant by “continuing motivation,” other than simply staying in a degree program (Fortus & Vedder-Weiss, 2014).

Some efforts should concentrate, then, on creating supportive environments within engineering to help retain students, while others focus on developing courses and projects that provide a window into what working life as an engineer is like. These broader initiatives should work in tandem with efforts within our courses. Many of these initiatives must take place at the administrative level to be effective (Menand, 2010; Muncey & McQuillan, 1996). Without administrative support and relevant incentives for individual professors, reform efforts often fade, although multiple studies also show that change cannot be

mandated in a top-down approach (Henderson, Beach, & Finkelstein, 2011). Individual professors should reshape their courses with these issues in mind. However, it can be difficult to bring these different facets of student experience into focus, and understand what is possible within a specific course.

Why the Transformative Experience?

We choose to use the transformative experience (TE) as a theoretical lens because it helps bring into focus many of the challenges touched upon here. Science education researcher Kevin Pugh defined the transformative experience as one that changes the student, causes shifts of perception in a profound way, and is distinguished by three qualities:

- 1) The student applies ideas from coursework to everyday experiences without prompting (*motivated use*);
- 2) sees everyday objects or situations through the lens of course content (*expanded perception*); and
- 3) values course content in new ways because it enriches everyday affective experience (*affective value*) (Pugh & Girod, 2007; Pugh, Linnenbrink-Garcia, Koskey, Stewart, & Manzey, 2010; Pugh, 2011).

There is congruence between these three qualities and the two-part problem as outlined above. Motivated use is a sign that students are interesting in using their engineering talents beyond school, expanded perception is an indicator that students are successfully “transferring” the knowledge to new contexts, and affective value asks how students feel about what they are learning.

Pugh and Girod explored the origins of TE in John Dewey’s work in a 2007 paper titled “Science, Art, and Experience: Constructing a Science Pedagogy from Dewey’s Aesthetics.” In that paper, they showed how the TE was developed from Dewey’s educational philosophy of learning through experience (Dewey, 1938), combined with Dewey’s observations on the power of our experiences with art (Dewey, 1934). Dewey describes art’s power as much more than temporary delight or distraction. The power of art flows from its ability to change how we perceive the world, to show us new significance in our experiences.

This is an aesthetic experience, one that can occur, not only with art, Pugh and Girod contend, but also in the natural world, and more to our purposes, with scientific ideas. The transformative experience is not about noticing great scientific ideas in everyday life mechanistically or rationally. It means allowing ourselves, in big ways and small, to get swept away by those ideas, to really feel the impact those ideas can have on us and the world around us.

We can have these aesthetic experiences with engineering concepts, as well.

Why Flow Visualization



Figure 2.1: Student captured example of a Hele-Shaw cell, an example of expanded perception

Sent: Tuesday, July 21, 2015 9:07 AM

Subject: Cool Flow Vis

Hey Professor Hertzberg,

I took Flow Vis about a year ago and it was a great class. Now every time I see cool fluid phenomenon in real life, I think about you and that class, so I thought I'd share this with you! I cracked my phone screen a few weeks ago and over that time, the air has started to creep between two plates in the screen. It's making a pretty neat Hele-Shaw Cell in only one direction instead of the typical radial style that you see.

Thanks for a great class,

David Zilis³

Any instructor would enjoy getting an email like this one, but beyond personal validation, what can we learn from it? Instead of seeing this email as individual feedback, we could see it as characterizing a specific kind of learning, the kind we most want to encourage. We should explore what causes a student, more than a year after a class, to contact an engineering professor with an example of the material he learned with her (Hertzberg, n.d.).

³ Photo and email used with permission.

This email also reveals that the student learned the material in a deep and meaningful way. That learning went beyond the short term memory needed to pass exams, and even a more durable form of learning that allows concepts to be recalled years later. This email is evidence that the student has had a transformative experience, demonstrating at least two of the three qualities of TE. This student is reporting, voluntarily, that he has had an expansion of perception: the student sees the world differently because of the content he learned in school. He perceives fluid phenomena “in real life.” He does not simply recognize that something interesting is happening: he can name it (“Hele-Shaw Cell”) and tell you why it is unusual (it is forming in one direction instead of radially). In addition, he finds meaning in noticing the Hele-Shaw cell. His affective value of the experience is shown in multiple ways: by capturing an image (Figure 2.1), and by sharing that image with his former professor. It is “cool,” and when he reflects back, it was “a great class.”

This student is echoing physicist Richard Feynman’s sentiment about experiencing scientific ideas with everyday objects:

I have a friend who’s an artist ... he’ll hold up a flower and say ‘look how beautiful it is,’ and I’ll agree. Then he says ‘I as an artist can see how beautiful this is but you as a scientist take this all apart and it becomes a dull thing,’ and I think that he’s kind of nutty... I see much more about the flower than he sees. I could imagine the cells in there, the complicated actions inside, which also have a beauty...the science knowledge only adds to the excitement, the mystery and the awe of a flower. It only adds. I don’t see how it subtracts. (Feynman, 1988)

Here is the crux of our problem. Not all students reach that expanded perception with a positive affective reaction. If we cannot fathom how increasing students’ perception could possibly detract, how can we help students reach a point where they can value, emotionally, that increased perception? Feynman’s artist friend is not the only one for whom knowledge induced the conversion of a beautiful experience into a “dull thing.” Consider this excerpt from Mark Twain’s *Life on the Mississippi*, as he describes how aspects of the river went from holding “romance and beauty” to only displaying important information pertinent to his job:

... that slanting mark on the water refers to a bluff reef which is going to kill somebody's steamboat one of these nights, if it keeps on stretching out like that; those tumbling 'boils' show a dissolving bar and a changing channel there; the lines and circles in the slick water over yonder are a warning that that troublesome place is shoaling up dangerously; that silver streak in the shadow of the forest is the 'break' from a new snag, and he has located himself in the very best place he could have found to fish for steamboats.... All the value any feature of [the river] had for me now was the amount of usefulness it could furnish toward compassing the safe piloting of a steamboat. (Twain, 1883)

Many of us discovered the poetry of the Mississippi River through Twain's writing. Ironic then, that he also captures the downside of expanding our perception. Twain wraps up this reflection by noting that other professions likely have the same problem, and ends by wondering, "doesn't he sometimes wonder whether he has gained most or lost most by learning his trade?"

Students can get stuck in a place where, like Twain, their expanded perception also means constant judgment. Perhaps this is a consequence of how we foster the critical thinking skills we value in engineering. Here is one student's response to a recent course survey that asked students to rank their agreement or disagreement with statements such as "technologies [related to the course] are beautiful" and "[course topic] moves me emotionally."

[The course topic] does not "move me emotionally" nor do I find it "beautiful." It is a functional tool that enables other technologies, and while I find it awesome, I frankly think that those are inappropriate questions for a survey about a class.

This is only one student's opinion, and somewhat contradictory (is "awesome" an emotional response?), yet it echoes an interesting problem for those of us attempting to deepen our students' engagement with the material we teach. On some level, this student believes the coursework should not be emotionally engaging, and we should not think about its beauty or lack thereof. We should not even ask about it.

Do we, in the structuring of our courses, assignments and exams, drive our students to Twain's starkly pragmatic view? Or do we support and encourage a Feynman-like fascination and joy in what they now know and can do?

Some may argue that we need not attend to what students feel about what they are learning, so long as they learn it. This attitude aligns with a common outsider view of science, that STEM fields require we be objective and without emotion. Yet, scientists and engineers often display passion or excitement for their work. If we design our courses away from viewing our fields with that passion, we misrepresent the potential of our disciplines. We have focused on only one part of the two part problem. We have taught students engineering without helping them see why they would want to become engineers.

Furthermore, if our courses foster judgmental attitudes only, we actually work against the goal of educating students. When judgment is foremost in our course design, we encourage a fixed mindset in our students, the notion that intelligence and other talents are fixed quantities for life. As psychologist Carol Dweck's work on mindsets has demonstrated, this makes our work a string of proofs of our worth, every learning task a test (Dweck, 2007). Such attitudes impede learning, because errors are exclusively points lost, not opportunities to learn from mistakes. Every low score is an indicator that the student does not belong in the field. Courses are often designed with few opportunities for students to explore or iterate as they learn, few opportunities to get feedback on their understanding outside of assignments that have direct impact on their final grades.

In contrast, Dweck has identified that people with growth mindsets perceive that they can grow and improve their own intelligence and talents. This turns assignments into learning experiences; it allows students to ask questions, not worrying whether they appear stupid. Since the development of any product or system requires iteration, it would make sense that our courses would encourage this mindset. Engineers need to question why something does not work.

Once we recognize the need to orient our courses so that students can both expand their perception and value that experience, the challenge becomes how to do this. A simple beginning is asking professors to share their own emotional engagement with their fields with their students. Often, professors express

their excitement and fascination with their work, yet this modelling of affective engagement seems to only reach a small subset of students.

One approach we investigate here is adding an explicit aesthetic dimension to the work. The student email about the broken phone was from just such a course: Flow Visualization, which asks students to create images of fluid flows that are both scientifically useful and artistic (Hertzberg, n.d.). Students present their work in class, and then write papers about the physics in their images. This course consistently garners unsolicited comments similar to the one cited here, e.g. “I’ll never look at the sky the same way.” These comments are shared with enjoyment, not annoyance. We find that the activities in Flow Visualization scaffold the expansion of perception in a way that encourages discovery and exploration, perhaps supporting the positive affective response (Goodman, Ewen, Harriman, & Hertzberg, 2015; Hertzberg, Leppek, & Gray, 2012).

In the classroom, STEM professors rarely acknowledge the beauty, elegance, or other aesthetic dimensions of their work beyond the “elegant solution.” These ideas are virtually never mentioned in formal assessments, even if those surveys are for the improvement of a course, and not for grading students. This notion, that aesthetics and emotional engagement might be important to learning, is so far removed from students’ current experiences that even asking about emotional or aesthetic reactions to a course can elicit irritation, as in the example quoted.

If we are sincere in our desire to stop the “leaky pipeline” of students leaving STEM majors, or simply to provide the best education possible, more study of the relationship between affect, aesthetics, and learning is needed. Passing rigorous exams is not enough; even expanded perception is not enough. Students can “see” their course content out in the world without appreciating it. Students may be motivated to use their new knowledge, but if that motivation is all extrinsic, it will likely fade as soon as those external rewards weaken.

In contrast, if we encourage students to value, affectively, those experiences and abilities, then they are more likely to persist through the STEM majors, and persist in STEM careers. Thus Flow Visualization, which clearly can foster the TE, becomes the starting place for this research, which helps us address the following research question:

How can educators promote student progress toward a transformative experience, and reliably measure progress toward that goal?

To address this two-part question we focus our work in three areas:

- 1) **Student Affect:** In the context of a specific engineering domain, what is the relationship between student affect and a concurrent expansion of perception?
- 2) **Teaching Methods:** What teaching methods and learning activities contribute to a transformative experience for students learning engineering?
- 3) **Perception:** What is the link between perceptual expertise and the transformative experience? How can we measure perceptual expertise in a particular engineering domain, such as fluid dynamics?

Chapter 3 – Literature Review

This chapter reviews the learning theories that are the basis for this research, as well as the concepts from psychology such as perception, that inform our work. We also describe how the connections between these concepts are represented in the framing of the transformative experience (TE).

Learning Theories

Learning How versus Learning Why

In the memoir of his childhood, neurologist and author Oliver Sacks notes that practical knowledge often far outstrips theoretical understanding in the sciences, sometimes for generations (2001). Education researchers sometimes draw a similar analogy between the discovery of knowledge in a discipline and the learning process of an individual (e.g. Strike & Posner, 1992). This idea, that we can develop hands-on knowledge of how something works long before we puzzle out why it works, may be fundamental to how human beings learn. Why, then, do we regularly attempt to teach students theory before the practice?

The answer is simple: it is faster. We do not have time to allow students to re-create thousands of years of human discovery, refinement, and invention, nor do students want to wander in the dark, with the feeling that instructors are hiding answers from them (Ackermann, 2001). However, what begins as an explanation of theory, with its rich structure and meaning, can become a series of shortcuts, devolving into disconnected pieces of information. Physicist and educator Edward Redish calls this the “dead leaves model,” in which students pick up information like dead leaves off the ground, with no comprehension of how they fit together or even that they were all attached to the same branch. How might we, instead, communicate about a discipline so that students perceive how all the leaves are connected on one “living tree” (Redish, 2003)? This is the challenge – to balance the need for experiential learning and the need to benefit from existing human understanding. This distinction has been studied in a number of forms, including Hutchinson’s classification of differences between deductive and inductive reasoning (Cloonan & Hutchinson, 2011; Obenland, Munson, & Hutchinson, 2013).

As instructors, we attempt to help students build their knowledge, skills, and abilities during their undergraduate years, with both experiential learning and appropriate direct explanation. In the process, it is critical that our students grasp both the “big picture” of how different aspects of their learning fit together and the details of how to use those skills in a specific instance. To begin this process, we need a common understanding of what represents a good educational experience.

Moving Away from Transmissionist Ideas of Education

John Dewey (1859-1952), who encapsulated his work in education with his 1938 *Experience and Education*, contended with one of the biggest education reform movements in history. In Dewey’s day, reformers wanted to move away from the traditional transmission approach to education, which viewed students as empty vessels that need facts and ideas dumped into them. The problem was that many of the new, progressive schools lacked a theoretical framework, and so educators worked from a position of negating tradition. Turning away from tradition did not provide a guide as to what they should turn *to*. Instead of logical, systematic reform, the baby was thrown out with the bathwater, as it were. Dewey critiqued this approach and suggested his theory of experience as a solution.

Dewey’s theory of experience, in contrast to transmission theory, argues that students learn best when new ideas and information connect to previous experiences, and learning occurs when the new ideas are gained via new experiences. Reform in schools, he argued, should be guided by this notion:

[the educator] must constantly regard what is already won [learned] not as a fixed possession but as an agency and instrumentality for opening new fields which make new demands upon existing powers of observation and of intelligent use of memory. Connectedness in growth must be his constant watchword. (Dewey, 1938, p. 75)

Anyone who has attempted to restart the study of a subject after a long gap in use will understand perfectly that prior learning is not a “fixed possession” but something that fades without use, without renewed connection.

The networked information age has brought with it challenges at least as great as those in Dewey's day. Advances in Information and Communication Technology (ICT) suggest progress, but books presented on tablet computers instead of in print, or lectures viewed as videos rather than in person, are still attempts to "deliver" education; they still follow a transmissionist view of learning. In fact, some critics argue that technology "amplifies the rote and authoritarian character" that typifies transmission (Papert & Harel, 1991). Adding technology does not automatically make a classroom more experiential. As Toyama notes, technology is only an amplifier, good or bad (2011).

The theory of learning through experience may seem obviously better; yet we find in practice many college classrooms where instructors make little effort to understand students' previous experiences, and who go about providing instruction with limited hands-on experiences with the material. Of course college requires certain prerequisites to be completed before students begin a particular course, and those prerequisites represent an understanding of students' prior experiences. However, this view keeps all knowledge within the purview of academia, and makes no attempt to connect to students' lives outside the classroom.

Notions of rigor are also used to support transmissionist thinking. Attempts to be more rigorous are often carried out by cramming more material into the course – in many engineering courses this results in more equations and more problems sets. While there is nothing intrinsically wrong with problem sets, plowing by rote through assignments can come at the expense of students' conceptual understanding, which entails connecting material to experience. Instead, students pick up Redish's "dead leaves" or what Dewey called "miscellaneous ill-digested information" (Dewey, 1938, p. 85), which they then have difficulty applying in new situations. However, when we design courses to provoke deep conceptual understanding, some breadth of content may be lost, as noted by Brown (1992) and Elby (2001), among others. For this reason, some argue that a focus on experiential learning is not a call for improved pedagogy, but instead an attempt to water down engineering curriculum. This is not the case.

“Rigorous” courses often result in students who, although they pass the course, cannot grapple with the ideas they have supposedly mastered. For example, students can “plug-and-chug” through problems involving Ohm’s law without being able to conceptually explain which light bulbs will be brightest in a given circuit (McDermott, 1993). The Physics Education Research (PER) community has found that after a semester of college physics, students are *less likely* to see the connection between their experiences of the real world and physics (Redish, 2003). As Lillian McDermott, one of the founders of PER, explains “once equations are introduced, students often avoid thinking of the physics involved” (1993). Courses that attempt to cover as many equations as possible thus fail on two fronts: the students who perform well in the course do not actually learn, and the students who do poorly frequently leave the discipline, because they have been shown that “this is all there is” to the STEM fields (Seymour & Hewitt, 1997).

Dewey defines bad educational experiences as those that have “the effect of arresting or distorting the growth of further experience”(1938, p. 5). That is, any experience that de-motivates students through poor representation of the material is not rigorous – it is merely bad instruction. Such courses tend to present engineering as math-centric and difficult, which it is, but they fail to demonstrate that engineering is also an intensely creative undertaking. This creativity is not communicated through lecture and more problem sets. Numerous studies document steady, high rates of attrition in our engineering colleges (X. Chen, 2013; Chesler et al., 2010; Lowell et al., 2009; Seymour & Hewitt, 1997). This attrition signals that we are, to use Dewey’s words, “arresting the growth of further experience” for many engineering students.

Critiques of Experiential Learning

Some critics of Dewey claim that attempts to connect to a learner’s past experiences thwart the teaching of new material outside of those experiences (A. L. Brown, 1992). This misses the point, that “Dewey’s position was intended to counteract the isolation of much of school learning from the familiar habits of childhood on the one hand, and adult occupations on the other” (A. L. Brown, 1992). Developing a course with the students’ prior experiences in mind does not require that no new experiences be introduced. In higher education, students (and their parents) increasingly want a strong

connection between formal schooling and adult occupations, because they wish to see an economic gain in return for the serious costs of attending college. Course design that considers students' past and (potential) future experiences is therefore becoming increasingly important.

Another criticism of Dewey's theory of experience is that the discovery process of the learner can lead to wrong conclusions about the world (A. L. Brown, 1992). We believe this to be a misreading of Dewey, who clearly understood the importance of a talented teacher to guide the process. While there should be room in our classrooms for the unexpected moment, we cannot rely upon such moments to occur spontaneously. As Dewey himself explains,

Improvisation that takes advantage of special occasions prevents teaching and learning from being stereotyped and dead. But the basic material of study cannot be picked up in a cursory manner. Occasions which are not and cannot be foreseen are bound to arise wherever there is intellectual freedom. They should be utilized. But there is a decided difference between using them in the development of a continuing line of activity and trusting them to provide the chief material of learning. (1938, p. 96)

The misunderstanding of experience-based learning has persisted, with strong critiques such as that by Kirschner, Sweller, & Clark (2006) who equate all forms of discovery learning with "minimal guidance" and conclude that scientists, while demanding solid evidence in their disciplines, depend on fuzzy intuition in their teaching. The former claim ignores the well-developed strategy of scaffolding, and the latter claim ignores the best work of the PER community and other discipline-based education research groups, efforts that are outlined by Henderson et al. (2011).

Experiential Learning as a Social Process

Experiential learning also acknowledges the social and cultural aspects of learning. Russian psychologist Lev Vygotsky (1896-1934) wrote primarily in the 1920s and 30s, although his impact outside of Russia was delayed by politics and translation. While there is a great richness to Vygotsky's work, here we explore two major ideas.

The first of these ideas is the *Zone of Proximal Development* (ZPD). The ZPD is “the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers” (Vygotsky, 1978, p. 86). Those working below their ZPD can complete tasks, but are not learning anything new; those learners attempting tasks above their zones will find these tasks impossible to accomplish, even with assistance. There is a necessary social aspect to Vygotsky’s definition: the ZPD is measured by working with someone else, not alone. Vygotsky heavily emphasizes the social nature of learning, and the ZPD concept has become “a fundamental component of the learning and education research literature” (Pea, 2004).

Although Vygotsky does not comment directly on the learner’s emotional experience in the ZPD, the ZPD can be related to idea of *flow*⁴ as defined by Hungarian-American psychologist Mihaly Csikszentmihalyi (1990). Csikszentmihalyi focuses on a person’s emotions during a task. These emotions can range from boredom with tasks that are too easy to anxiety or frustration with tasks that are too difficult. *Flow* occurs when the task is challenging but not impossible, and is defined as a state of optimal enjoyment, usually occurring when a task “stretch[es] the person’s capacity and involve[s] an element of novelty and discovery”(Csikszentmihalyi, 1997, p. 110).

This element of discovery suggests an activity in which the person is learning, so although Csikszentmihalyi did not originally define *flow* during overt learning tasks, these ideas clearly apply to learning. Thus, *flow* is more likely to occur within the ZPD. In fact, some diagrams representing both these concepts look remarkably similar, as shown in Figure 3.1. Research of *flow* has expanded beyond individuals to social settings, such as athletic teams or musical ensembles (K. Sawyer, 2007), with an emphasis on how creative innovations develop best in heterogeneous groups. *Flow* is also discussed in research on motivation and perseverance (Shectman, Debarger, Dornsife, Rosier, & Yarnall, 2013).

⁴ Since much of our research pertains to fluid physics, often described as fluid flows, we italicize the psychological construct *flow* to distinguish it from the physical phenomena that is the content of the courses we studied.

Since working in the ZPD typically means working with assistance, education research has developed the term “more knowledgeable other” (MKO) (e.g. Mariage, Englert, & Garmon, 2000), which can be a teacher or tutor, but may also be a more knowledgeable peer or even a technological aid. The MKO can provide some assistance, hints, encouragement or even similar examples. This sort of assistance allows us to fully map out a student’s ZPD, since, as Vygotsky points out, two students who score about the same level in a content area may score very differently when given the same assistance (Vygotsky, 1934/2012, p. 198)⁵. Similarly, the term “scaffolding” is often used in conjunction with ZPD (although Vygotsky does not use this term), to express strategies of assistance-giving, either in the format of the tasks or in the behavior of the MKO to help the student work in his ZPD consistently without giving too much assistance (e.g. J. S. Brown et al., 1989; Podolefsky & Finkelstein, 2007). When successfully employed, scaffolds are eventually removed, and the learner can accomplish the task without them. If misapplied, learners may find they cannot recognize the knowledge needed for a task without the scaffolding to cue them. Developing appropriate scaffolds is thus a major challenge in creating an effective learning environment.

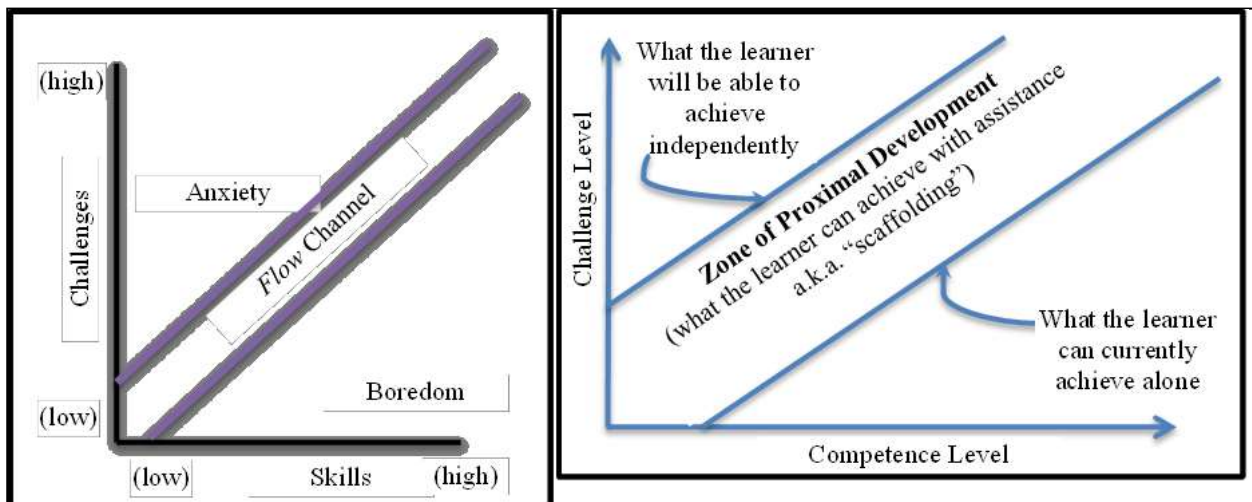


Figure 3.1 Representations of *flow*
 Based on Csikszentmihalyi (1990), and the Zone of Proximal Development based on Morsink (2013)

⁵ This also foreshadows the “2 Sigma Problem” identified by Bloom, which observes students with 1-on-1 tutoring achieve learning gains two standard deviations (“2 sigma”) higher than classmates in a 30:1 student-teacher ratio classroom (Bloom, 1984).

The second idea from Vygotsky that we will discuss is the interplay between the structure of a thought and its function (Vygotsky, 1934, p. 219). We might say that the thing being learned cannot be adequately taught without considering how it will be used. Vygotsky's work focuses on the relationship between a child's development and how she is instructed. He specifically notes that these cannot be treated as independent factors, when the interplay between structure and function, what is learned and how it is learned, had such a huge impact in the learning of the children Vygotsky studied. Similarly, STEM courses that are structured with little regard to how the knowledge will eventually be used may be poorly received and ineffective. Although the work of learning a STEM discipline is different than the professional work in a STEM discipline (Kirschner et al., 2006), common feedback from engineering employers is that new hires do not know how to "be" engineers upon graduation (National Academy of Engineering, 2012), a difficulty we can begin to remedy by recognizing that all learning is "situated" (Wenger, 1998).

Situated Learning and Communities of Practice

Vygotsky's research presages current work in situated learning. Lave and Wenger pioneered the idea that all learning is contextualized, or situated, within a group of people who share a set of practices, which are naturally implicit to the formation of the group. Such a group is called a community of practice; learning is understood to be situated within that community (Lave & Wenger, 1991). Similarly, situated cognition⁶ is the idea that learning always exists within a context, and that many aspects of a content area are communicated by "the ambient culture rather than [by] explicit teaching" (J. S. Brown et al., 1989). A system of cognitive apprenticeship can help facilitate the ability to generalize concepts from one setting to another. J.S. Brown et al. point out that the classroom itself becomes a particular community of practice, which bears little resemblance to that of the related professional discipline. The classroom itself is a form of scaffolding: "students may come to rely, in important but little noticed ways, on features of the

⁶ Situated learning and situated cognition are closely related concepts, and sometimes used interchangeably. For example, an article titled "Situated Cognition and the Culture of Learning" (J. S. Brown et al., 1989) is retitled "Situated Learning and the Culture of Learning" on John Seely Brown's website. (http://people.ischool.berkeley.edu/~duguid/SLOFI/Situated_Learning.htm)

classroom context, in which the task is now embedded, that are wholly absent from and alien to authentic activity” (J. S. Brown et al., 1989). Accordingly, if instructors do not recognize the role of the context of the classroom, they may never work to remove the aids implicit in the environment to ensure that students can work outside of that structure. It is important, during the learning process, to expose students to the “authentic activity” of the related discipline to help students make that transition. As J.S. Brown et al. note: “[g]iven the chance to observe and practice in situ the behavior of members of a culture, people pick up relevant jargon, imitate behavior, and gradually start to act in accordance with its norms.” Acknowledging the impact of such informal learning practices is the start of utilizing them deliberately.

Constructivism and Constructionism

Within these communities of learners, we also recognize how individuals are constructing knowledge. Constructivism, Piaget’s epistemology, builds upon the idea that learning is an element of, and subordinate to, development of the whole learner, and begins with the idea of an operation (Piaget, 1964). In contrast to the transmission view of learning, Piaget argues that to know something is not to make a mental copy of it, but rather to know something is to be able to act upon it. “An operation is thus the essence of knowledge; it is an interiorized action which modifies the object of knowledge” (p.176).

At the highest level of Piaget’s stages of development, these operations can be completely abstract, manipulating physical or imagined objects. Piaget points to two kinds of experiences that shape a learner’s development, and consequently their learning. The first is physical experience. We can act upon objects, see the consequences, and know something new about the objects. The second kind is logical mathematical experience. For example, when a child uses beans as counters to do early math problems, the child is not learning about beans, but about the property of an action: adding, subtracting, ordering, etc. Once the action is interiorized, the child no longer needs the beans in order to perform the operation.

Much like Vygotsky’s ZPD, Piaget recognizes that a learner must be “in a state where he can understand” the new information, and that “he must have a structure which enables him to assimilate this

information” (Piaget, 1964, p. 180). Piaget’s key concept is assimilation, which he defines as “the integration of any sort of reality into a structure.” Structures are built in the mind, from simple to more complex, through logical mathematical experiences, and assimilating new knowledge requires active transformation of the material by the learner. Here, Piaget emphasizes the importance of the learner’s active work with the new knowledge. In Piaget’s description, new knowledge is often incompatible with what the learner “knows.” The process of assimilation includes reconciling the old with the new and coming back into equilibrium. These key processes, building structures in which to assimilate new knowledge, point us to a characteristic of good educational experiences. The ability to pull back from the immediate situation and recognize what has changed is vital. Learners need time to reflect.

This leads to Seymour Papert’s notion of constructionist learning. Papert (1928-) is a South African computer scientist and educator, whose seminal work in education at the MIT Media Lab published in the 1980s and 1990s, has shaped how computer science is introduced to children. While Papert prefers to give extensive examples to show what constructionism does, rather than define what constructionism is (Papert & Harel, 1991), a working definition of constructionism is that knowledge is constructed in the mind, and this more readily occurs when we construct something in the world.

Constructionism echoes Dewey’s theory of learning-through-experience, and in addition explains why transmission methods sometimes work – the learner is building the ideas in her mind by interacting with an artifact, such as a text, or listening to a lecture. Although this may be a more difficult task than building knowledge through some sort of hands-on experience, it can still be accomplished.

In an insightful essay, Edith Ackermann, a colleague of both Piaget and Papert⁷, compares Piaget’s *constructivism* and Papert’s *constructionism* (and includes some analysis of Vygotsky’s ideas, which Ackermann characterizes as the socio-constructivist tradition) (2001). She notes that Papert’s constructionism is “more *situated*” (emphasis in the original) than the theories of either Vygotsky or

⁷ Her online profile at MIT (<http://web.media.mit.edu/~edith/>) notes that Ackermann worked under Piaget and had Papert on her dissertation committee.

Piaget. Constructionism places greater importance in being able to adapt in specific circumstances, which vary by culture, location, and even an individual's personality. This adaptation does not always require a transition from a concrete instance, to an abstraction, to a new concrete instance. Papert sees that learners can adapt directly from one concrete instance to another. Typically, Papert's work stems from people interacting with a specific artifact and, as Ackermann puts it, examines the "initiative the learner takes in the design of her own 'objects to think with'" (p.5). Constructionism emphasizes, in contrast to constructivism, the need for learners to immerse themselves in the whole environment to fully grasp what they are learning.

Rather than pose these theories as mutually exclusive, we choose to view them as describing different phases of learning. Our understanding of experiential learning, then, contains cycles for both reflection and immersion, time for both individuals grappling with ideas and groups socially constructing knowledge.

P-prims versus Misconceptions

In a growing movement that began around 1970, the physics community in higher education has started taking a hard look at its own teaching methods, laying out theoretical frameworks, and then systematically testing them in practice. Researchers found that emphasizing problem-solving does not automatically result in conceptual comprehension, and instead "equations become crutches that short-circuit attempts at understanding" (Van Heuvelen, 1991). As a result, more interactive teaching methods were introduced, and these new methods correlated with better outcomes on standardized concept inventories (Hake, 1998). However, many of these methods also correlated with worsening attitudes about physics, specifically, and science, generally. For example, one tactic involves eliciting students' misconceptions about physics principles, confronting those misconceptions in an attempt to change students' thinking, and then resolving the differences between the two. This method correlated to improved assessment outcomes, but also correlated with students' belief that physics was somehow not about "the real world" (Adams et al., 2006; Perkins & Adams, 2005).

So, this “elicit, confront, resolve” tactic is giving way to acknowledgement of the students’ “phenomenological primitives” or p-prims for short (Hammer, 1996a). P-prims begin as “minimal abstractions of common phenomena,” which students likely have not fully articulated (DiSessa, 1993). These very small scale nascent ideas are functional; that is, they allow students to successfully navigate the world, and are loosely organized in layers. In a situation where the misconception might be called “motion implies a force,” a teacher can call attention to the difference between a car with an engine, which keeps it moving, and an initial push on a ball with no continuing force. The student can then realize his previously-unverbalized p-prims, using the correct vocabulary about force and momentum (Hammer, 1996b). This distinction is subtle, but creates a starting point of building on students’ experiences rather than “tearing down” what they already know – it allows the teacher to guide a Piagetian assimilation of the knowledge. In contrast, telling students to ignore or distrust their p-prims causes cognitive dissonance, which results in a disconnection between their experiences of the real world and physics, the discipline that describes the actions of the real world.

We cannot insist that students think about a subject in one way if it contradicts their prior experiences. Teaching, then, is a nuanced process of helping students see how new things are connected to things already in their experience. Without this process, odds of students attaining the *expansion of perception* quality of the transformative experience become much worse. Students need opportunities to immerse themselves in the material, and time to step back and reflect on it. They need time to grapple individually with it, and time to work collectively to build their understanding.

Concepts from Psychology

Perception

In psychology, perception is often discussed as the linkage between sensing the world around us and our subjective experience of it. Perceiving is one step above “sensing,” which is the name for our senses

reporting about the world and our states within it to our nervous system. Perception implies a level of processing of the raw sensory input, but that processing can take place very early in the nervous system, such as when neurons in the eye perform some processing of the visual input as the information is passed to the optic nerve. There is not a clear division between sensing and perceiving in that case. At other times, our nervous system is clearly sensing certain inputs that we do not consciously notice. For example, we may not perceive our heart rates unless there is a sudden change (Saper, 2002). With this example, it becomes clear that we typically require conscious awareness or noticing of something to call the act perception. The phrase “sensory perception” is used by researchers when they focus on the conscious perception of sensory input. For example, education researchers use “sensory perception” when they want to connect students’ sensory experiences to their perception of the content they are learning (Reiner, 2009). However, a search of the psychology and neuroscience literature shows that these fields tend to avoid this blended phrase.

Many psychological studies have focused on perception related to individual senses such as auditory (Schnupp, Nelken, & King, 2011) or tactile (Tiest & Kappers, 2009). In particular, visual perception, and the visual processing in the brain associated with it, has been studied by psychologists and neuroscientists (Gauthier, Skudlarski, Gore, & Anderson, 2000; Rossion, Collins, Goffaux, & Curran, 2007; Tanaka & Curran, 2001; Tanaka & Taylor, 1991), and by computer scientists interested in modeling perception and computer vision (Moeslund & Granum, 2001; Palmeri, Wong, & Gauthier, 2004). The study of perceptual expertise builds upon what is known about visual perception mechanisms. One example of perceptual expertise is human face recognition. Most people become “experts” in face recognition as they develop (Adolphs, Tranel, Damasio, & Damasio, 1994; Gauthier, Curran, Curby, & Collins, 2003). Visual perceptual expertise in other areas, such as identifying cars or birds, has also been explored, as a means for understanding visual perception (Gauthier et al., 2000).

Visual perceptual experts more quickly perceive the relevant information in their environment, and instead of mentally categorizing something at a basic level, and then a subordinate level, can often go

directly to subordinate level identification (Tanaka & Taylor, 1991). For example, a novice bird watcher, in attempting to identify a bird, might see a bird and think *song bird* → *finch* → *red-and-brown finch with certain features* and then have to utilize a bird book to further identify the species as *purple finch*. The expert sees the bird, immediately identifies it as *purple finch* and can move on to questions about whether the bird is nesting, or why it has not migrated at the normal time of year. The novice must move through basic categories first to find the correct subordinate-level category, if they are able to identify at that level at all. The expert can often go directly to that level, as shown by studies measuring event-related potentials in the brain (Herzmann & Curran, 2011; Tanaka & Curran, 2001).

In areas other than face recognition, visual perceptual expertise has been found to be context or subject specific, rather than a general trait. That is, people who are visual experts for one content area are not necessarily good at seeing details everywhere. For example, Nodine and Krupinski found that medical technicians who excelled at reading medical images were not better than average at other visual expertise tasks (Krupinski, 2000; Nodine & Krupinski, 1998). This suggests that visual perception can be enhanced with practice and is context-sensitive. It can be learned in a specific domain. In work described here, we explore how students develop visual perceptual expertise for images related to in fluid physics.

Visual perceptual expertise can contribute to other forms of expertise that a person may develop, for instance, when recognizing abstract concepts learned in new contexts. For example, experts in physics, for example, are shown to sort problems in different, more useful ways than novices (Chi, Fletovich, & Glaser, 1981; Chi, Glaser, & Rees, 1982). In these studies, Chi and her colleagues found that while physics experts grouped problems according to the “major physics principle governing the solution,” novices relied on surface features (e.g. the diagrams all include pulleys) or by the keywords present in the wording of the problem (1981, p. 125). This example demonstrates shows how experts’ perceptions are developed in particular ways. Like the medical technicians in the Nodine and Krupinski studies mentioned above, when working those problems the physics experts learn which aspects of a problem

they must attend to, and which they can safely ignore. Experts thus maximize the use of their working memory, which appears to have a finite capacity⁸.

Novice students often do not perceive which details in the problems are most important, and are more likely to place the highest importance on those aspects that are graded. If the numerical answer to a problem is all that is assessed, students will pay more attention to getting that number right than to the acquisition of deeper conceptual understanding. By learning to measure perceptual expertise, we could create courses that deliberately train students' perceptual expertise. It remains to be seen how these two types of expertise, visual and analytic, might be related, and how they might be connected to the TE definition of expanded perception.

Motivation Theories

In the psychology and neuroscience literature, differing motivations are used to explain why similar subjects (or even the same subject) react differently in what appear to be identical situations. The common understanding is that differences in individuals' motivations explain the variations in behavior that we see, even when we believe their situations and goals to be identical (Berridge, 2004). Psychologists most often examine motivation in the context of learning new behaviors. Repeated behavior may be habit, but because learning new things requires exerting effort, learning new things must be motivated behavior.

Yet the reverse need not be true. Could learning be routine for some learners? Could they be continuing their education out of habit or lack of other options? This seems more likely for students prior to college, but once enrolled in higher education, most students have choices, and many of them choose paths other than STEM. Motivation theories address not only what triggers activity, but also what "sustains" it (Higgins, 2012, p. 232). Therefore, understanding motivation theory can help us to create better environments for students, so that they can see the value in staying.

⁸ There is serious debate on precisely what that capacity is, and the oft-cited figure of 7 ± 2 (G. A. Miller, 1956) has been challenged (Shiffrin & Nosofsky, 1994).

Current education models generally motivate students by awarding grades; students figure out what is important through this process. The implication is that we value only what we measure. Most students have been enculturated to this norm during their K-12 experiences. In fact, professors who attempt to break out of this paradigm can find themselves inundated with questions of “will this be on the test?” or “does this count for a grade?” The result is that students tend to disengage from lessons they realize will not “count.” Despite students’ habituation to this system, we need to break away from this strictly carrot-and-stick approach to motivation, because it perverts the true goals of education. Maladaptive behaviors, such as avoiding courses or instructors perceived to be “too hard,” or cheating on assignments⁹, demonstrate that the ultimate outcome has become the grade rather than learning. Little wonder that professors become exasperated that many students will not engage the material for the joy of doing so.

In higher education, the near-term “stick” (a bad grade) is not well aligned with what might be called the long-term “carrot” – being able to perform well in a professional setting after graduation (Christiansen, Johnson, & Horn, 2010; Wagner, 2008). There is no clear link between doing well in formal learning settings and doing well in professional settings. This misalignment weakens the perception of reward. The hedonic principle (carrot-and-stick approach) to understanding motivation is both reductive and lacks the ability to explain the breadth of human behavior. Students do not only seek pleasure and avoid pain, because then no one would finish challenging courses that require scores of hours to complete assignments (Higgins, 2012). If we want to understand and encourage the *motivated use* of content as quality of the transformative experience, we must develop a more robust understanding of motivation.

Neurobiological Motivation

Attempts to locate a dedicated motivation region of the brain (Olds, 1969), or specific motivation neurons (Valenstein, Cox, & Kakolewski, 1970), have met with little experimental success, and more

⁹ Some students no longer regard copying answers from solutions manuals to be cheating, but rather what they must do to survive a course (J. Tsai, Kotys-Schwartz, & Knight, 2015; J. Y. Tsai, 2015, p. 194+), which might be interpreted as valuing the grade more than the learning.

recent work to locate a motivation neurotransmitter is also proving challenging (Berridge, 2004). Motivation seems to be a messy, emergent construct that arises from more than one kind of activation, much the same way memory encoding has been shown to not reside in either the hippocampus or the cortex, but in both (Atallah, Frank, & O'Reilly, 2004). What neuroscience can tell us about motivation is that there is a distinction between *liking* and *wanting*; that is, they can be disassociated from each other, not only in the psychological sense, but also in a neurobiological sense (LeDoux, 2012). In animal trials, rats can be made to want a sugary drink even as they show a disgust reaction while drinking it (Pecina & Cagniard, 2003). This research is being used to better understand drug addiction in humans (Berridge, 1999), and can also help us understand students' relationship with their learning. Students can like a subject without feeling motivated to study it.

One popular motivation theory separates extrinsic motivation, represented by the hedonic principle, from intrinsic motivation. Under Deci and Ryan's Self-Determination Theory (Deci & Ryan, 2008b), intrinsic motivation comes from engaging people with three things.

- 1) People need to feel a sense of *competence* or mastery. They need to feel like the task they have been given is not beyond their skills.
- 2) People need to have some measure of *autonomy* in how they complete the task. If there is only one right way that will be accepted, this will limit the motivation they experience.
- 3) People need a sense of *relatedness* or how the task is connected to other goals the person has in mind. Some writers have called this third point *purpose* (Pink, 2009).

For example, a particular combination of student and course might fit Self-Determination Theory if 1) the student's recent experiences result in the new material in the course being within her ZPD (competence); 2) there is latitude to solve problems or complete projects in more than one way (autonomy); and 3) the student can easily see how this course both builds on previous courses and sets her

up to succeed in future work she hopes to do (relatedness/ purpose). Self-Determination Theory is being used to study a range of phenomena including exercise (P. Wilson, Mack, & Grattan, 2008), employee pay (Gagné & Forest, 2008), and most relevant to this research, education (Vansteenkiste & Simons, 2004).

Flow and Regulatory Fit

Flow would seem to describe the perfectly intrinsically motivated activity. Csikszentmihalyi found that creative people from a variety of disciplines described their work as intrinsically motivated (p. 109). Elements of *flow* activities are 1) clear goals, 2) immediate feedback, 3) balance between challenge and skill, 4) action and awareness merge, 5) distractions are excluded from consciousness, 6) no worry of failure, 7) self-consciousness disappears, 8) sense of time becomes distorted, and 9) the activity becomes autotelic, or an end in itself (p.111-113). One can imagine a student (or group of students) becoming engrossed in coursework – debugging a program, building a robot, or even writing a paper – and experiencing *flow*. If they experience this “optimal enjoyment” in coursework, their *motivated use* outside the classroom as part of the TE seems far more likely.

Somewhat counterintuitively, Deci and Ryan repeatedly observed that offering individuals extrinsic rewards for something they would have done for intrinsic reasons diminishes later motivation to perform the same act once the reward was removed (e. g. Deci & Ryan, 2008a; Deci, 1971). The implications for higher education and the workplace are concerning. College is typically a formative period in life, a time when students form habits of mind and discover their passions. By using extrinsic rewards, such as grades, are we training students to be poor employees, the kind that never takes initiative, who see problems but say “not my job?” By using grades, are we dismantling the potential for *flow* in their chosen fields?

We could do away with grades, as some colleges have done,¹⁰ but perhaps we do not need that radical a change. Motivation, once again, is a bit more complicated than the intrinsic/extrinsic dichotomy. Advancing a theory he calls *regulatory fit*, psychologist Tory Higgins has explored how offering rewards that suit the task can reinforce motivation, even when the person is intrinsically motivated according to Self-Determination Theory (Higgins, Cesario, Hagiwara, Spiegel, & Pittman, 2010). This is why employees can have moments of *flow*, even though they are being paid for their work. For example, many software developers who are paid to code also work on open-source projects at home for free (Ariely, 2008, p. 81), the same sort of scenario that Deci and Ryan tested. In this case, the pay, which would be termed an extrinsic reward under Self-Determination Theory, is a *salient incentive* (Wright & Panksepp, 2012), and in line with the employee's expectations. If the employee discovered she were being paid significantly less than her co-workers for the same sort of work, she would no longer perceive her pay as fitting the task, and be de-motivated by thinking about her paycheck. This demotivation also occurs if the employee learns that those workers who do significantly less work are rewarded at the same level she is. Likewise, students may be de-motivated if they perceive an instructor grading unfairly or offering preferential treatment to others in class.

The concept of regulatory fit goes farther, and argues that we are more motivated when the action, our reasons for doing the action, and means of performing the action are aligned (Higgins et al., 2010). This is why office workers can be motivated for rote tasks such as stuffing marketing envelopes with overtime pay, but volunteers at a food pantry would be insulted if offered payment to load boxes with food. Behavioral economist Dan Ariely characterizes the differences between activities that can be motivated with concrete rewards as governed by market norms and those that cannot as governed by social norms (2008). Some students may be motivated by grades (market norms) or by helping a study group with homework (social norms), and we can see what happens when these norms mix detrimentally in

¹⁰ See Evergreen State College, Olympia, WA. (<http://evergreen.edu>) Also, the Narrative Evaluation System at University of California, Santa Cruz, until 2001 (<http://admissions.ucsc.edu/apply/parents-and-guardians/prospective-students/grading.html>).

collaborative assignments. Social loafers will do the minimum needed to get the grade, while their aggravated teammates pick up the slack to complete the project (K. Sawyer, 2007), a clear conflict of market norms in a situation where developing stronger social norms might be called for.

While this interesting distinction may be useful, it does not explain actions that are less embedded in social contexts. The student working on his own to try out an idea from class, a clear case of *motivated use*, is not reacting to market norms or social norms; he is not experiencing a transaction, in Ariely's sense of the word. Regulatory fit, then, offers the best understanding of motivation in this context.

Perhaps it would help to think of motivation as situated as well, since, as Higgins explains, there is no "all-purpose energy." Attempting to motivate students by recasting serious activities as "fun" will backfire (Bianco, Higgins, & Klem, 2003). Instructing people to be serious about activity they perceive as fun is likewise de-motivating. This seems to support other findings, where people were observed to do worse on activities requiring creative insight when offered a monetary reward (Pink, 2009), offering some interesting insights into the nature of creativity.

Creativity

A common historical mythos of creativity in our culture is that of the lone genius, but numerous studies show that good teams are actually far more productive, and those famously independent inventors or artists nearly always had a community working with them (K. Sawyer, 2007). Another myth about creativity is that we must wait for it to strike. There is a long history of invoking the Muse for inspiration, and part of the *flow* experience is often an odd feeling that we do not know where the ideas are coming from. However, most big breakthroughs come to people "out of the blue" only after months or years of work on the problem from different angles, trying and failing in different ways (Wagner, 2012). So if these myths are not true, what exactly characterizes creativity?

In his book *Out of Our Minds: Learning to be Creative*, British educator Ken Robinson defines imagination, creativity, and innovation as follows:

- Imagination is “the ability to bring to mind events and ideas that are not present to our senses.”
- Creativity is “the process of having original ideas that have value.”
- Innovation is “the process of putting original ideas into practice.” (Robinson, 2011, p. 220)

These distinctions are useful because the act of implementing a creative idea requires a different skill set from the act of generating and selecting the idea in the first place.

Creativity is rarely linear. As Keith Sawyer explains in *Zig-Zag*, creativity often comes “in tiny steps, bits of insight, and incremental changes” (2013, p. 2). So the real drawback of offering a concrete reward for something that requires creativity is that creativity requires meandering a bit, and those rewards encourage attempts to aim directly for the target. Creativity requires connecting ideas we have not already connected before¹¹, constructing new thoughts. Sometimes these incremental changes are failures, with each new attempt an iteration.

The creative process needs room to try things, sometimes failing in the attempt. As the Irish playwright Samuel Beckett exhorts us, “try again, fail again, fail better.” In many ways, the *motivated use* quality of the transformative experience is the process of students tinkering with and testing the new things they have learned. Creativity gets better with practice, and innovation requires perseverance.

Perseverance and Similar Constructs

When confronted with failure, some students will try again and others will quit. Several constructs address this phenomenon, e.g., tenacity, perseverance, and determination. MacArthur Fellow and psychologist Angela Duckworth defines *grit* as perseverance plus passion for a difficult long-term goal. Her work has discovered that generally, individuals who self-identify as being the most passionate and determined about their defined goal are more likely to achieve it. While even Duckworth admits that additional study is needed to determine whether grit will turn out to be a “mere epiphenomenon,” it seems

¹¹ Neurobiology also informs this idea, since neurons that “fire together wire together” in what is known as Hebbian learning (Aisa, Mingus, & O’Reilly, 2008). Perhaps creativity is related to how our brains to wire together new neurons.

clear that a person's belief about his capabilities can play a key role in how much he will persevere (Duckworth, Peterson, Matthews, & Kelly, 2007, p. 1100) . That belief system is something we can directly address with students.

Stanford psychologist Carol Dweck has spent decades researching just such a belief system, calling that belief system a *mindset*. A student with a fixed mindset believes he has fixed level of abilities, talent, and intelligence; he can make maximal use of them, but he has “a certain amount and that's that.” As a result, students with fixed mindsets find that “their goal becomes to look smart all the time and never look dumb” (Dweck, 2007). One immediate consequence is these students rarely ask questions in class. When they encounter difficult concepts, they believe that they simply may not have enough talent or intelligence to ever understand, rather than recognizing the need to iterate. Very bright students tend to have this trouble when their early education failed to challenged their abilities fully (Kennedy-Moore & Lowenthal, 2011). Such students find challenging courses to be challenges to their identities. At the first C on a major exam, they begin to wonder, “am I really the engineering type?” Indeed, if students have always been told they are full of potential and praised for things that came easily to them, they are less willing to risk failure, to risk losing that part of their identity, and as a result are more likely to quit (Kennedy-Moore & Lowenthal, 2011). The typical way engineering courses are scheduled reinforces this mindset. Students are tested, told their scores (with partial credit given for partially demonstrated skills), and then sent onto the next topic, with few opportunities to iterate, regardless of actual comprehension.

Growth mindset, on the other hand, is the belief that abilities, talent, and intelligence can be grown “through effort, good teaching, and persistence” (Dweck, 2007) . Growth mindset is *not* the belief that everyone “can be Einstein, but they believe everyone can get smarter if they work at it” (Dweck, 2007). In a growth mindset, there is less risk in asking a “dumb question,” in trying a new way to solve of problem, or sharing with fellow students what you're struggling with. In growth mindset, a student's identity is rooted in being a seeker of knowledge, not in already knowing it. Even so small a change as encouraging students to insert the word “yet” can shift their mindset when talking about not being able to

solve a problem (Dweck, 2007). “I don’t know how to solve this—yet.” Clearly this mindset is needed for both the zigzag process of creative thinking, and to be *gritty* enough to complete an engineering degree. How can we foster the growth mindset?

Play and Aesthetics

There are practices, backed by research, that stretch imagination and creativity, which anyone can use to increase their likelihood of having useful, original ideas (K. Sawyer, 2013; R. K. Sawyer, 2000). Most of these techniques require a cycle of immersion in a task, follow by reflection (harkening back to Papert and Piaget), where this reflection is in the form of *meta-cognition*, or understanding our personal thought processes. These techniques emphasize continual learning, especially in fields unrelated to existing expertise, helping students purposefully become more observant of the world, make things, and, significantly, *play* (e. g. K. Sawyer, 2013; Wagner, 2012).

Play may sound like a simple act, but as a phenomenon enacted by both individual children (as noted by Vygotsky) and whole cultures (such as anthropologist Clifford Geertz’s notion of *deep play* (1973)), it is clearly important in human life. As Vygotsky observed, playing with a concept is the first way we gain knowledge of it. Closely linked to *flow*, play is typically a self-motivated, immersive activity, the original autotelic experience. The ability to go at things with gusto, simply because they delight us, often fades in adulthood, perhaps because, as Csikszentmihalyi comments, “you start to get ashamed that what you’re doing is childish” (quoted in Pink, 2009, p. 128). We should combat the notion that only children play, since it is essential to experiencing new ideas. By playing, we understand new ideas by pushing boundaries and being more imaginative with them. In play, we rekindle our creativity. If we wish students to engage their studies creatively, we must then engage them to see, at least some aspects of what they do, as playful.

The connection between play and aesthetics has been noted for centuries (Schiller, 1794), and the human impulse for both play and the creation of items for aesthetic purposes is often linked (Hein, 1968;

Upton, 2015). While aesthetics is most commonly studied in the context of fine art, it is easy to substantiate the aesthetic qualities of scientific and engineering ideas. Scientists from Poincaré to Feynman have commented on the beauty of their work, something that both inspires and motivates them (Girod, Rau, & Schepige, 2003).

In engineering, we most often comment on aesthetics in the context of design, when the end user of the product or system must be taken into consideration (Brezing A.N., Brezing, & Lower, 2009; Dennis & Al-Obaidi, 2010; French, 1980; Freudenthal, Roy, Ogrey, & Gates, 2009; Goncher, Johri, & Sharma, 2010; Hekkert, 2006; Huang, Eades, Seok-Hee Hong, & Chun-Cheng Lin, 2010; Ilmberger, Schrepp, & Held, 2008; Miyata, Umemoto, & Higuchi, 2010; Moon, 2010; Moss & Gunn, 2009; Rodriguez, Choudhury, & Rodriguez, 2010). Aesthetics has only recently become a studied consideration for the graphics we provide to students as learning aids (Kohl, Rosengrant, & Finkelstein, 2007; Loverude, Heron, & Kautz, 2010; Reiner, 2009; Rosengrant, Van Heuvelen, & Etkina, 2009). Pointedly, there is no explicit handling of aesthetics as the motivation for engineers themselves.

Summarizing Our Use of the Transformative Experience

In passing, the many concepts reviewed here may seem unconnected – a jumble of factors to consider in a study of engineering education. What is needed is a theoretical lens that brings into focus the disparate ideas on aesthetics, perception, and motivation, while supporting the work with a strong learning theory foundation. We contend that this lens is the transformative experience. The transformative experience (TE) is a profound learning experience, with three distinctive indicators: 1) motivated use, 2) expanded perception, and 3) affective value (Pugh & Girod, 2007; Pugh et al., 2010; Pugh, 2011). In fact, the transformative experience has also been called the transformative, *aesthetic* experience (Pugh & Girod, 2007), which reveals part of why this construct is useful in our work. The TE's basis in Dewey's theory of experiential learning, connected with an understanding of the motivational power of aesthetic experiences, makes it a strong framework with which to contextualize this research.

Chapter 4 – Instructional Contexts

This chapter describes the three courses that were analyzed in this research. Since teaching methods are central to the first line of inquiry, these descriptions note the format, learning goals, assignments, and other details of these courses. Our impetus for this investigation began with a course titled “Flow Visualization” (Flow Vis). This unique technical elective is described first. It shares content area with the second course, a required course in “Fluid Mechanics.” Flow Vis shares teaching methods with the third course, “Aesthetics of Design” (Aes Des). The relationships among the three courses are illustrated in Figure 4.1.

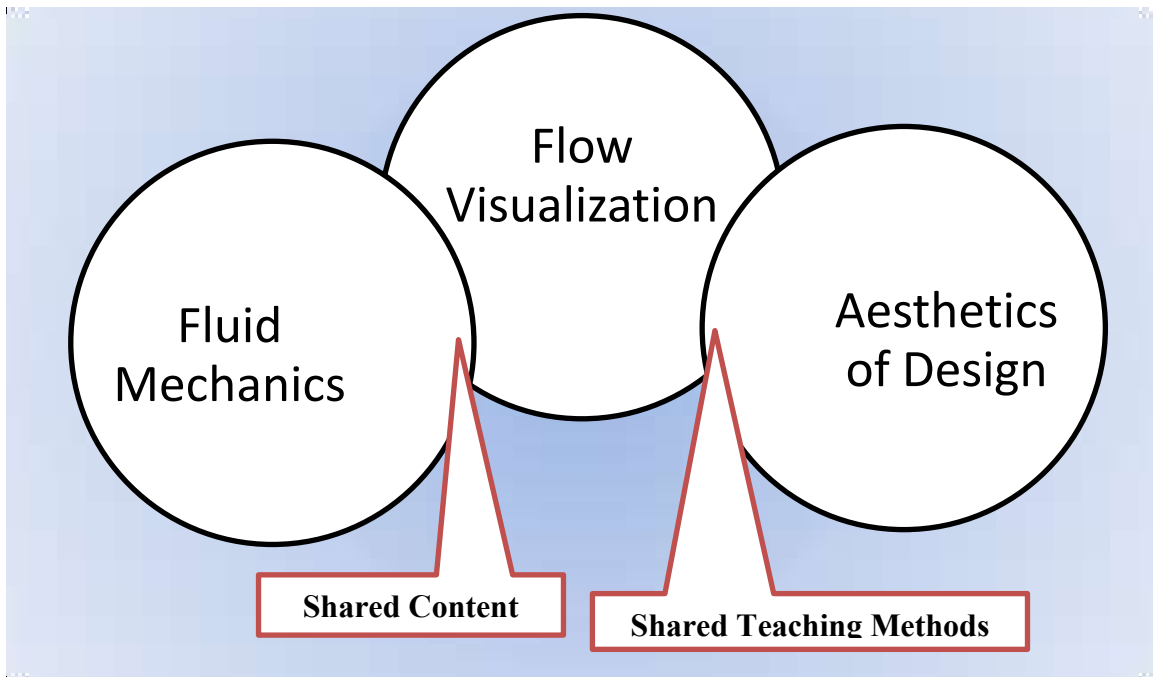


Figure 4.1: The relationships between the three courses explored in our research.

Course Description – Flow Visualization

Flow Visualization (Flow Vis) is a three-credit technical elective. It brings together engineering and fine arts photography or film students who cooperate to produce aesthetically pleasing and scientifically useful images of fluid flows. This course admits both undergraduates (primarily juniors and seniors) and graduate students. Engineering majors use the course as a technical elective, and have the required Fluid



Figure 4.2: Image by students Emily Howard, Preston Wheeler; Colliding water jets result in a 'fishbone' instability, 2012.

Mechanics course as a prerequisite. The art/film majors count Flow Vis as part of a studio requirement. There are typically 40-50 students in the class, with about 25% of the students coming from non-engineering majors. Flow Vis has been offered most spring semesters, beginning in 2003. Most years it has been taught by a single instructor, with a teaching assistant who helps with grading. New in 2015, the course is being offered in the fall semester. Figures 4.2 and 4.3 show sample student work from the course.

The stated goal of the course is to allow engineering students to tap into the rarely-acknowledged motivational power present in the aesthetics of fluid flows, and

simultaneously encourage the art students to learn a bit about fluid physics while practicing the method of experimentation. That is, engineers are asked to behave like artists by capturing images with visual appeal, and artists are asked to behave like scientists by documenting their experiments. To foster the

disciplinary crossover, a secondary goal is to have these students work with each other, and thus learn from each other's point of view.

Some class sessions are lecture-oriented, especially early in the semester, when topics include imaging basics, light-matter interaction, and fluid mechanics. Later class sessions focus on students presenting their work. There are six projects over the course of the semester that can be either still photographs or short videos. Three of these assignments are completed individually. The first assignment is called "Get Wet." Part of the lesson of this first assignment is to demonstrate the

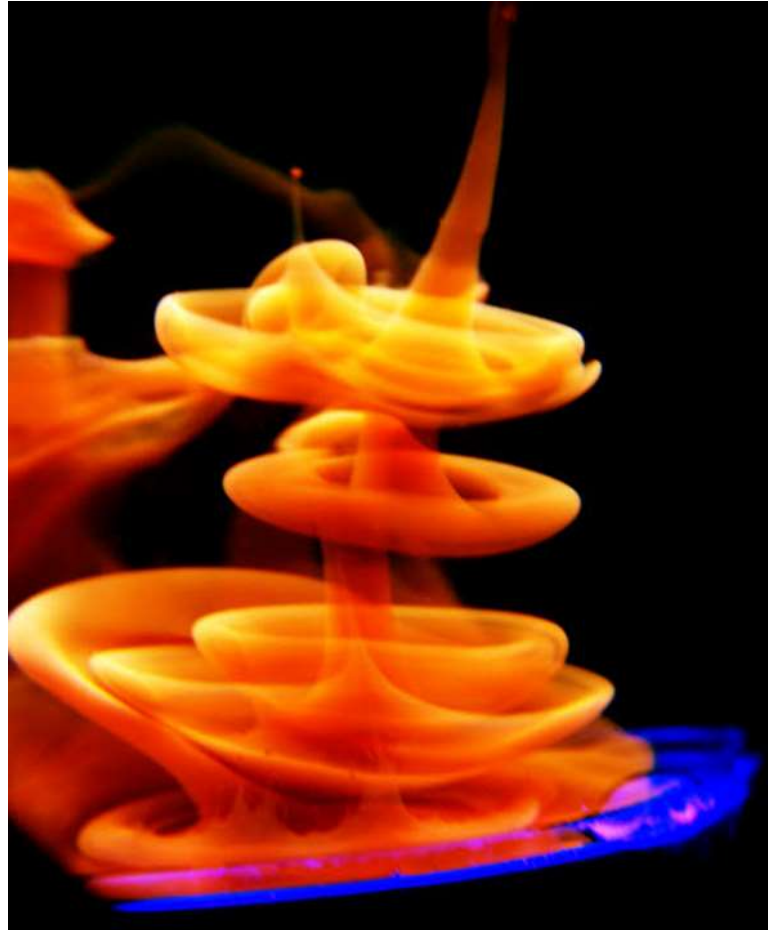


Figure 4.3: Image by student Jacob Varhus. Dyed mineral oil injected into clear mineral oil forms layers of vortex rings. 2013.

challenge of controlling a flow while documenting it visually. For two assignments, students also independently photograph cloud formations throughout the semester. Aside from the cloud images, the only specification for image content is that it must document fluid mechanics. For the remaining three assignments, students work in teams. To share resources and expertise, the teams are formed using the Comprehensive Assessment of Team Member Effectiveness (CATME), a tool which now also includes team-forming professor-customizable questionnaires (Layton, Loughry, Ohland, & Ricco, 2010). For each team assignment, students have individual creative control of their images, while supporting

teammates in reaching their objectives. We call these resource teams, as students act as resources for each other, but are not creating a group project.

The various student images are presented during class. The professor and other students comment on the image. To foster honest, encouraging critique and to ensure that all students participate, students may bring their laptops and can log in anonymously to offer comments. Discussion spans fluid physics and aesthetics. The professor often supplies keywords that can be used to research the phenomena present in the image.

The written explanation of the image is due one week after the presentation. In one to four pages, students provide the context for their images such that someone else could attempt to re-create them. This paper includes apparatus, materials, and photographic techniques used, and an explanation of the phenomenon demonstrated. Art students write generally about the physics involved, while engineering students are expected to estimate the appropriate non-dimensional properties, such as the Reynolds number, and provide time and spatial resolution based on flow speed and field of view. Graduate engineering students cite technical, refereed literature and write at a professionally publishable level. All students are expected to cite references.

The course culminates in a show in the Engineering Center lobby. Students are encouraged to submit their work to various competitions, and their work is displayed on the course website (www.colorado.edu/MCEN/flowvis/). The grading standards emphasize taking each assignment seriously (including the written explanation), collaborating in groups, and providing thoughtful feedback. However, the detailed points-based grading used in other engineering courses is not employed. Any student who fully participates can expect an A. Only a few students each semester fail to do so.

Course Description - Fluid Mechanics

Fluid Mechanics is a required third year mechanical engineering course, at the University of Colorado Boulder, and at most engineering schools and for a variety of other engineering fields, including environmental, civil, and aerospace engineering.

Fluid Mechanics is a three credit course offered every fall and spring in multiple sections, using a highly analytic, mathematical approach. The course catalog describes the course as follows: “Examines fundamentals of fluid flow with application to engineering problems. Explores fluid statics and kinematics; conservation equations for mass, momentum, and energy; Bernoulli and Euler equations; potential flow; laminar and turbulent viscous boundary layers; laminar and turbulent pipe flow; and compressible fluid flow” (University of Colorado Boulder, 2015)

Although still considered a lecture course, most instructors at CU have augmented this typical “talk and chalk” course with several innovations. For instance, the professor does not require a specific text, and in the syllabus recommends buying one of the “many fine used texts available online.” The syllabus also states that “contemporary issues will be covered using up-to-the-moment information from the web.” This is not only a boon for budget-conscious students, but also a deliberate teaching strategy, so that students see more than one way to approach a concept. An example of improved classroom practice is the use of concept quizzes, administered through a classroom response system (colloquially called “clickers” since the students’ responders look like simplified TV remotes). Another way students must express conceptual understanding is through quick in-class writing assignments called “minute papers.” Many instructors also take advantage of websites where students can ask each other questions, in addition to the TA and the professor. Some expose students to how fluids can be presented visually with a “Flow Vis of the Day” to begin each class meeting.

Fluid Mechanics also stresses the importance of professionalism, including academic integrity, and the syllabus includes an outline of how to correctly write an email to the professor. One facet of this

professional emphasis can be seen in the detailed structure for homework assignments. There are ten items expected on each problem, starting with a succinct problem statement and ending with a verification or “reality check” – a written explanation of why the answer makes sense. Students are not discouraged from studying together, but are expected to turn in their own work. Grading is fairly traditional: homework counts for a relatively small portion of the final grade, and exams generate the bulk of the points.

Course Description – Aesthetics of Design

Aesthetics of Design (Aes Des) is a three-credit technical elective, offered for the first time in the summer of 2014 during a compressed, summer session that met Monday–Friday for 3.5 hours a day for three weeks. All students were in the mechanical engineering department, divided roughly into two thirds undergraduates and one third graduate students. Students designed and built projects while developing a *design aesthetic*. Three instructors offered insights from multiple disciplines, including those outside mechanical engineering (in this case, electrical engineering, computer science, photography, and music).

Instructor Goals and Logistics

The learning objective for Aes Des was to have students reframe their understanding of design to include aesthetics. The resulting projects were a secondary consideration, a vehicle for helping students change their assumptions about design tasks and to pursue a personal aesthetic. As a result, a central, but implicit, goal of the instructors became creating a safe environment where students could take risks with their designs without worrying that a failing project meant a failing grade. As long as students were engaged in the process, they were considered to be succeeding in the course, even if the final project “crashed and burned.”

The participatory nature of the course meant that lectures were structured to encourage students to reflect, respond, and share new ideas. Early topics introduced different design aesthetics and covered

broad background, including the theory of design, historical approaches to design, and how design paralleled art in the 20th century. Other class sessions explored the aesthetic properties of styles from Romanticism and Gothic Revival to current trends like “pixelated” objects and steampunk. Case studies from art, industrial design, architecture, music, and engineering included successful designs such as the Treepod¹², Philips Pavilion¹³, Piaggio Vespa¹⁴, Box Appetit¹⁵, REMLshelf¹⁶, Papei 101¹⁷, Socket¹⁸, Zendrum¹⁹, Oyster Pail²⁰, London Telephone Booth²¹, John Deere Tractor²², and the Apple II²³.

Lectures were interspersed with interactive workshops. For example, one activity, called an *empathetic design thinking* workshop²⁴, had each student articulate what he or she wanted to another student, who then had to outline a design for the first student. The goal of this was discover the underlying motivations of the first student (the interviewee), so that the second student could alter and improve the design without losing its core. This required the interviewer to listen with empathy to understand not only what the interviewee wanted to have, but why she wanted to make it. The activity also served an intended secondary function, helping teammates get to know each other. As the course progressed, organized whole-class activity tapered off to allow for more individual or team work.

Each instructor gave the lectures or guided the activities most closely affiliated with his or her expertise. That instructor was responsible for that portion of the materials, documentation, and content. The instructors started the course with a mutually agreed-upon general outline, and made detailed plans

¹² http://www.shiftboston.org/competitions/2011_treepods.php

¹³ http://en.wikipedia.org/wiki/Philips_Pavilion

¹⁴ <http://www.piaggiouusa.com/history.html>

¹⁵ <http://www.black-blum.com/products/box-appetit/>

¹⁶ <http://design-milk.com/remlshelf-artistic-wood-shelving/>

¹⁷ http://en.wikipedia.org/wiki/Taipei_101

¹⁸ <https://www.kickstarter.com/projects/unchartedplay/socket-the-energy-harnessing-soccer-ball>

¹⁹ <http://www.zendrum.com/>

²⁰ http://en.wikipedia.org/wiki/Oyster_pail

²¹ http://en.wikipedia.org/wiki/Red_telephone_box

²² https://www.deere.com/en_US/corporate/our_company/about_us/history/timeline/timeline.page

²³ http://en.wikipedia.org/wiki/Apple_II_series

²⁴ Based on Stanford d.school's gift-giving exercise (<http://dschool.stanford.edu/dgift/>).

roughly two days in advance. The design of the course had to be adaptive, both for the shortened semester format and for the needs of the particular students. Activities were added, removed, lengthened or shortened based upon the reception of topics in previous days. To facilitate this on-going instructional design, instructors met daily for 30-60 minutes after the class. Fortunately, their complimentary mix of expertise and teaching styles simplified keeping the course organized even while it remained fluid.

Outside of the post-class meetings, the instructors communicated primarily by email. They took turns reading the students' daily blog posts (see description below), flagging any that caused concern, and relaying those posts to the appropriate instructor. Reading and evaluating longer reports (which accompanied the design review presentations, see below) was done in the same manner, with one instructor taking lead on a particular set of reports, and relaying any issues to other instructors as needed.

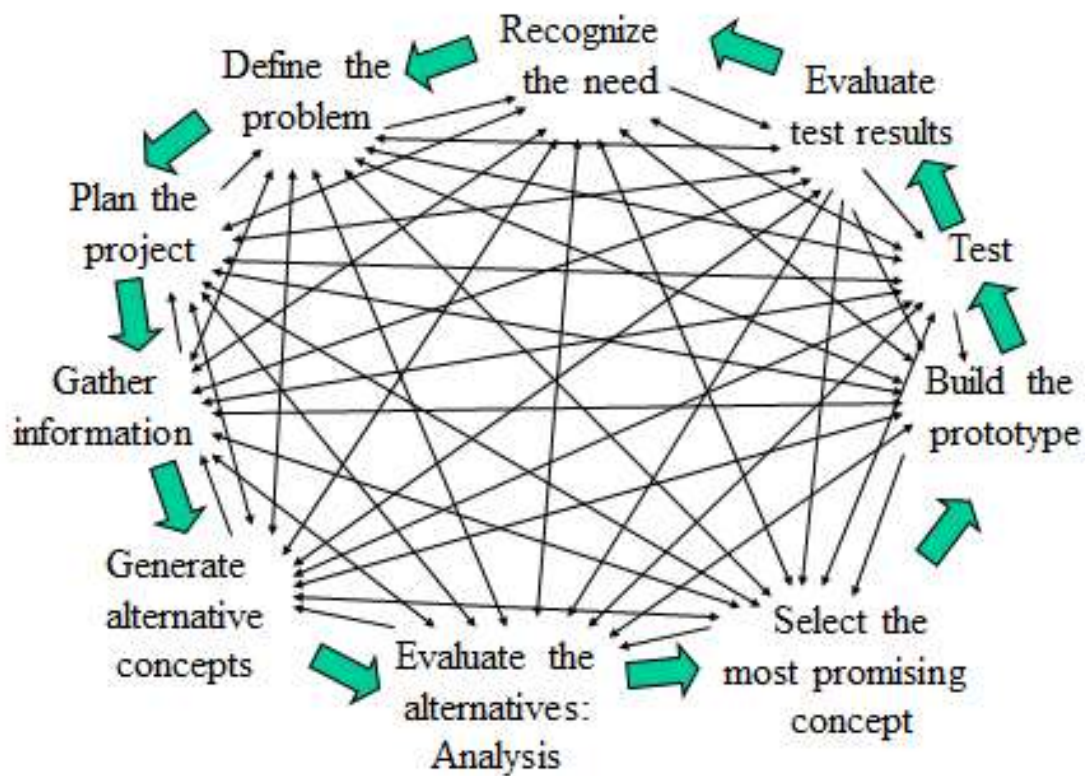


Figure 4.4: The Iterative Design Process (Hertzberg & Louie, 1999), used with permission

As the course progressed, the instructors concluded that their emphasis had to be on the iterative nature of design. Students were understandably eager to jump to the building phase of their work, often without reflecting on their choices. Many course activities had aims such as identifying users' needs, researching existing solutions, vetting a promising solution and possible alternatives, and problem-solving or redesigning once a solution failed to materialize as hoped. In lectures, workshops, and individual contact with students, the instructors worked to underscore the fluidity of good design, and encourage students' willingness to change, update, or otherwise iterate in their work. Figure 4.4 is a graphic used in class to explain the iterative, and often messy, process of design(Hertzberg & Louie, 1999).

Team configuration

Students were assigned to teams using a CATME (www.catme.org) questionnaire (Layton et al., 2010), with 97% of the students participating. Instructors customized the categories so that students with similar commitment levels to the course and similar schedules were more likely to get grouped together. Race and gender information was used to ensure that no student from an underrepresented demographic was isolated on a team. Also, teams were formulated to have diverse backgrounds and skills among the team members. At the end of the course, students were invited to use the CATME peer evaluation tool (Ohland et al., 2012), with 88% of the students participating. Those results were released to students at the end of the course.

Class assignments

The Project

Students were given the task of designing an object and building it, according to their personally defined design aesthetic. The only requirement was that the object be dynamic in some way. (We should note that logistics constrained students' projects in other ways. Students owned their final projects, so they were expected to buy the materials. Most students faced financial constraints. Due to time



Figure 4.5: Samples of student projects

From top going clockwise, LED Poi by Patrick Maguire, The Grub Shrub by Max Anderson, Watch Box by David Bidwell, and Sea-t Anemone by Chelsea Young

limitations, ordering parts or materials was not always feasible. Also, students were not able to secure projects on-site except in 4 ft³ lockers, which created a size constraint for some students who preferred to have larger projects on-hand during class.) Examples of student projects are shown in Figure 4.5.

The Blog

Students were asked to create a new blog post each day, where they were expected to record design decisions and progress, reflect on influences on their aesthetic choices, and note other thoughts related to

the course, a practice noted to help with reflective learning (H. L. Chen et al., 2005). These were publicly visible²⁵ and took the place of a physical design notebook for many students.

Design Review Presentations and Reports

Each of the three weeks ended with a design review presentation and accompanying report. The first week featured a brief preliminary design review. In week 2, for the critical design review, many students presented the difficulties they were facing and sought input from both instructors and other students. At the end of the course, a final review was presented publicly. The instructions for the final paper, due the day after the public review, asked students to not only detail traditional metrics, such as construction, costs, and functionality, but also address whether aesthetic goals were met. They were encouraged to reflect on the entire process of the course, describe their work on the project, and comment on what they learned along the way.

²⁵ Some students have chosen to remove their blogs, but many are still available at: <http://aestheticsindesign.blogspot.com/>

Chapter 5 –Methods for Interpretive Studies

This chapter describes the research methods used to address the first two lines of inquiry of the primary research question:

- 1) Student Affect: In the context of a specific engineering domain, what is the relationship between student affect and a concurrent expansion of perception?
- 2) Teaching Methods: What teaching methods and learning activities contribute to a transformative experience for students learning engineering?

Using fluids as the “specific engineering domain” in question, we implemented to two methods to gain insights into student affect and expansion of perception: 1) Based on previous work, we utilized an existing survey, and 2) we interviewed students. We began collecting these data for Flow Vis and for Fluid Mechanics. As our work progressed, we realized these types of data would also be useful in exploring our second line of inquiry. When the opportunity arose to investigate an aesthetically-oriented design course with pedagogy similar to Flow Vis, we applied the same methods there.

One benefit of having both survey and interview data from these student populations is the ability to clarify and verify findings between the two types of data. For example, responses to open-ended survey items were used to support and reinforce conclusions drawn from the Aesthetics of Design interviews, described in Chapter 6. Also, when numerical results from the survey were inconclusive, interview data provided a window into why we received those responses.

Survey Methodology – Item Response Theory

Surveys are used in myriad ways in education. To construct and evaluate surveys for these courses, we have built on previous work that utilized Item Response Theory (IRT) (Hertzberg et al., 2012; M. Wilson, 2005). IRT works from the assumption that we are attempting to measure a single characteristic, called a latent trait or variable. Surveys that measure more than one trait are viewed as multiple

instruments administered together, with each instrument requiring separate validation and reliability testing (M. Wilson, 2005).

In this case, our goal is to measure perception of fluids with the Fluid Perception Survey or FluPerS for short. The original work of defining this construct, creating a concept map, and validating the survey was presented in 2012, prior to the start of this study (Hertzberg et al., 2012). This earlier work provided the foundation for our current analysis, as both fluids perception and affective response were documented. That is, prior to identifying the transformative experience as a theoretical lens, this work already addressed two of the three indicators of TE: expanded perception and affective value.

The FluPerS was used unchanged from the 2012 study for both the Flow Vis (spring semesters of 2013 and 2014) and Fluid Mechanics (fall 2013 and spring 2014). The survey was re-worded for a design course, and used in May 2014 for the Aesthetics of Design course.

Survey Data Collection and Analysis

Survey questions were coded into Qualtrics online survey software and delivered through an email invitation sent to all students enrolled in the courses being studied. This occurred in both the first and last weeks of the course to obtain a pre/post data set. Emails were addressed as from the professor with replies directed to the researcher. A small homework grade was given for completing the survey, but students could elect to opt-out and still receive the points by asking the researcher.

Participants

Survey participants (n=145) were all students at the University of Colorado Boulder. They were 75% male, 25% female. Most were undergraduates (83%), as Fluid Mechanics is an undergraduate course, but Flow Vis is cross-listed as a graduate class, so a small but meaningful percentage (17%) were graduate students. Although we did not take demographic data, they are presumed to roughly reflect the College of Engineering which reported 9.1% international students (no racial designations), 69.0 % white, 8.9%

Asian American, 8.8% Latino/Latina, 1.2% African American, 1.2% Native American and 0.4% Pacific Islander, in 2014.²⁶

Survey Questions

The Fluids Perception (FluPer) Survey had both closed response and open response questions. The closed response questions are shown in Table 5.1.

	FluPerS Questions – Numerically Scored	Post survey alternate wording
Q6.1	I want to study fluids	
Q6.2	The study of fluids is useful to society	
Q6.3	Studying fluids is useful to me, as an engineer or an artist	
Q6.4	I can study fluids	
Q6.5	I expect this be a difficult course	This was a difficult course
Q6.6	I expect this to be a fun course	This was a fun course
Q8	Fluids are interesting	
Q9	Visualizations of fluid flows are very beautiful	
Q10	Visualizations of fluid flows are fun	
Q13	How often do you notice and think about fluid flows outside of classwork?	

Table 5.1: Numerically scored questions from the Fluid Perception (FluPer) Survey

These questions were scored on a 5-point Likert scale from “Completely agree” (1) to “Completely Disagree” (5). The exception was Q13 “How often do you notice (and think about) fluid flows outside of classwork?” For this question, students were given the following choices: Hourly (1), Several times a day (2), About once a day (3), A few times per week (4), A few times per month (5), A few times per year (6), and Never (7).

Many of the open response questions are paired with a closed response question, allowing students to explain their answers. Here are the open response questions, with their partner questions noted, where applicable. Note that the question numbering does not reflect the order they were presented on the survey.

²⁶ CU Planning, Budget, and Analysis: <http://www.colorado.edu/pba/div/enrl/>.

	FluPerS Questions – Open Response	Associated closed response Q
Q7	What do you think is interesting about fluids?	Q8
Q11	If you find fluid flows beautiful, what do you think is beautiful about them?	Q9
Q12	What do you find fun about visualizations of fluids?	Q10
Q14	Please give two different examples of common fluid flows that you have noticed.	Q13
Q15	Do you feel you can describe the physics of fluids that you encounter? Do you ever want to?	
Q16	What do you think and feel about fluids?	

Table 5.2: Open response questions from the Fluid Perception Survey (FluPerS)

The FluPerS questions were revised to use in the design course survey. Where possible, the design questions mimicked the fluids survey questions. Because it was a new course, the Aesthetics of Design survey included additional open response questions in the post-course version to capture student feedback on different features of the course. This also allowed us to explore student responses regarding the teaching methods used in Aesthetics of Design. See Table 5.3.

	Design Perception Questions	Both/ Post only	Open / Numerical Score
6.1	I want to study design	Both	5 pt scale (agree/disagree)
6.2	The study of design is useful to society	Both	5 pt scale (agree/disagree)
6.3	Studying design is useful to me, professionally	Both	5 pt scale (agree/disagree)
6.4	I can improve my sense of design through study	Both	5 pt scale (agree/disagree)
6.5	I expect this to be a difficult course	Both*	5 pt scale (agree/disagree)
6.6	I expect this to be a fun course	Both*	5 pt scale (agree/disagree)
8	What do you think is interesting about design?	Both	Open
7	What do you want to accomplish in this course? What do you hope to learn or do in this course?	Both*	Open
9	Well-designed objects or systems are beautiful	Both	5 pt scale (agree/disagree)
11	What makes a well-designed object beautiful	Both	Open
10	Design is fun	Both	5 pt scale (agree/disagree)
12	What do you find fun about design	Both	Open
13	How often do you both notice and think about design outside of classwork?	Both	Hourly /Several times a day /About once a day / A few times a week / A few times a month / A few times a year / Never
14	Please give two examples of time you have noticed design	Both	Open
15	Do you think about design principles involved in the examples listed above? What were they?	Both	Open
16	What do you think and feel about design?	Both	Open
20	What is the most exciting or interesting thing you will take away from this course?	Post	Open
21	What is the most useful thing you learned in this course	Post	Open
22	Was blogging helpful? What was good about it, and what would have made it a better experience?	Post	Open
23	How did the promise of publication of your work motivate you, compared to the usual graded feedback?	Post	Open
24	You were asked to both design an artifact and to think about it in specific ways (consider the blog assignments). Was the balance effective?	Post	Open
25	What would you have done differently if this was a full semester class?	Post	Open
26	If this course were presented as a full semester course, would you have preferred devoting more time to (select all that apply)	Post	Historical aesthetics / design theory and interaction theory / smaller, hands-on projects / other (fill in)
27	What did you learn that was new to you?	Post	Open
28	Is there anything else you think this class should include	Post	Open
29	Is there anything you think should be removed from the class?	Post	Open
	*Question slightly reworded for the post course survey		

Table 5.3: All survey questions used in the survey, rewritten for Aesthetics of Design.

Survey Analysis

To evaluate the surveys, we matched pre/post pairs, setting aside any surveys without a counterpart. For each respondent, we compared the pre- and post- responses to each closed-response item, which were numerically scored.

We then performed the Wilcoxon Signed Rank Test, a non-parametric test intended to be used in repeated measures or matched pairs data such as ours. The goal of this test is to assess whether the population mean *rankings* are different between the pre- and post- sets of data when the distribution does not pass tests for normality. With this test we can ask questions such as: did the student least interested in the course remain near the “bottom” of the class, or did that student move up the rankings? We also calculated the Sign Test, a less sensitive test that is also non-parametric. The Sign Test is only attuned to the direction of the difference between the two sets of data. In other words, this test focuses on the sign of the delta between the two sets of data.

Responses to the open-ended questions were set aside and reviewed with the interview data.

Interview Methodology - Phenomenography

There are many approaches to collecting, organizing, and analyzing interview data. We chose to employ phenomenography, a methodology Professor Diana Laurillard of University College London has called “the best hope for a principled way of generating teaching strategy from research outcomes” (Laurillard, 2002, p. 71). The goal of a phenomenographic study is not to describe how students solve particular problems, but rather describe their *ways of seeing* the problem or their *experience* of solving the problem. The basic unit of inquiry in phenomenography goes by a number of names: “ ‘ways of conceptualizing’, ‘ways of experiencing’, ‘ways of seeing’, ‘ways of apprehending’...” (Marton & Pong, 2005, p. 336), all of which directly support the line of inquiry we are investigating for the transformative experience. Since learning is often a creative “zig-zag” process (K. Sawyer, 2013), rather than a proscribed series of steps, we knew we were not attempting to find a “recipe” for transformative

experience. Instead, we wanted to understand TE as a phenomenon with many variations, and discovering variations is a strength of this methodology (Marton & Pang, 2013). Phenomenography has been recognized as a good methodology by other physics education researchers (DiSessa, 1993) as well as by engineering education researchers when there was a need to “explore experiences and perceptions with the aim of understanding how to assist students as a group to develop more useful approaches in their learning in particular contexts” (Baillie & Douglas, 2014, p. 3).

Interview Data Collection and Coding

The interview data was collected and analyzed as follows:

- 1) Students were recruited through emails forwarded by course instructors to the current students. Sometimes labeled “pre” interviews for brevity’s sake, initial interviews were typically conducted during the first or second week of the course. The process of contacting willing subjects and scheduling interviews created this delay. The interviewer then contacted students again in the last 3 weeks of the course to schedule the follow-up interview, which was typically conducted in the last week of classes. Interview participants (n=17) were 76% male, 24% female, all undergraduate students. Further characteristics have been withheld to avoid re-identifying those participants.
- 2) Interviews were conducted in small study rooms, reserved at a library or in an engineering building, convenient to the students’ normal routines. Following an approved protocol²⁷, the interviewer obtained written consent from the subject, and then recorded audio of the interview, while taking hand written notes. Students were compensated \$20 for each interview.
- 3) Interviews followed a semi-structured format: the interviewer attempted to cover the following topics, but also allowed the conversation to flow and used follow up questions to allow subject’s responses to naturally cover these topics as much as possible.

²⁷ IRB protocol #14-0038.

- a. Engineering Identity - Do you identify as an engineer? What does that mean to you? (For Flow Vis, the art/film students were asked: Do you identify as an artist / filmmaker?)
 - b. What expectations do you have the course / Did the class meet your expectations?
 - c. Do you think the format of this class will help or hinder (did it help/hinder) your learning? How?
 - d. How does/did the course compare with others you have taken?
 - e. Experiences with collaboration (generally / specific to this course).
 - f. Experiences with visualization (generally / specific to this course).
 - g. (Post only) What's the most significant thing you will take away from the course?
- 4) Interview recordings were transcribed and subjects were de-identified.
 - 5) The first stage of evaluating the interviews was to listen to them while reading the transcripts, partially to verify accuracy of the transcriptions, but also to detect larger themes.
 - 6) The second stage of analysis was to create tables of these larger themes by subject. Each subject's comments were summarized in "pre", "post", and "delta" columns. Notes in the "delta" column attempted to summarize major changes in attitude and motivation by the subject or strong themes that stayed consistent between the two interviews. With the smaller Aes Des data set (n=4), analysis shifted to how to represent the recurring themes. With the rest of the data we continued as follows.
 - 7) Transcriptions were loaded into QSR International's NVivo 10 software, and major themes were coded at the following nodes:
 - a. Motivation (or demotivation) as influenced by:
 - i. Grades (desire for a good grade)
 - ii. Social forces (desire to work with teammates or desire to help society)
 - iii. Aesthetics (desire to create a look/feel or enjoying a particular look/feel)
 - iv. Functionality (desire to make something function correctly or enjoying how something works)

- b. Expansion of Perception – explicitly noticing something “in real life” that is related to course material.
 - i. Unprimed/Primed – comments expressing an expansion of perception without a question prompting them were flagged as “unprimed”
 - ii. General – several students commented that being an engineer was about “seeing how things work” or “viewing life as systems.” This was not specific to the courses in question, but seemed relevant to flag within the data.
- 8) A second coder was engaged to re-code six interviews. After comparing coding and updating the code index, the two coders were found to be in agreement in 93% on average (Cohen’s kappa between 0.51 and 0.84) at the main node level (motivation, expanded perception), and the remaining interviews were coded.

Survey Open Response Coding

We examined only the surveys that had pre/post pairs. After several readings, the following themes emerged:

- **Practicality:** interest in fluids generated by usefulness, general application, or specific areas of application, such as aerodynamics.
- **Complexity:** interest in fluids linked to their chaotic nature and the challenge of solving the problems, including specific mentions of the unsolved Navier-Stokes equations and modeling techniques.
- **Ubiquity:** interest in fluids resulting from their being “everywhere” or “all around us” or even “inside us.”
- **Aesthetics:** interest in fluids fueled by their appearance, beauty, often expressed as the subjects’ enjoyment in looking at the flows.

Responses from Q7 (What do you think is interesting about fluids?) and Q16 (What do you think and feel about fluids?) were coded on these four nodes in the most detail. Q15 (Do you feel you can describe the physics of fluids that you encounter? Do you ever want to?) responses were tallied for both parts of the question using Yes / No / Depends as categories.

Validity and Reliability

There are many differing standards discussed when reviewing interpretive studies, and the same method may be used by different researchers employing different methodologies (Baillie & Douglas, 2014). One way of framing a qualitative study's quality and relevance that has become more prevalent in engineering education research is Qualifying Qualitative Research Quality or Q3 (Walther & Sochacka, 2014). There are six facets to this framework, six interrelated ways to evaluate the procedures for both data collection and data analysis. These evaluations help us *validate* and *gauge process reliability* (Walther, Sochacka, & Kellam, 2013). The first is *theoretical validation*, which asks about the fit between social reality we are examining and the theory being generated. In this case, our theoretical lens is the transformative experience, established by other researchers (Pugh, 2011; Wong, Packard, Girod, & Pugh, 2000). We are in less danger of attempting to force social reality to fit our theory, because we did not begin with an *a priori* theory and then search for examples. Instead, we had numerous examples of TE before having a name for it; it was the unsolicited comments from students that inspired our research direction.

The second facet of Q3 is *procedural validation*. It asks how well the features of the research design “improve the fit between the reality studied and the theory generated.” While phenomenography generally relies on interviews, we examine the interview data in light of the survey findings, both quantitative and open response. This mixed-methods approach allows us to keep an “authentic view” of students’ experiences, rather than focus solely on the particular group of students who were interviewed.

The third facet, called *communicative validation*, draws attention to the integrity of participants’ meanings. Are those meanings maintained through the various analyses? Students’ words should not be taken out of context to create a point, and differences of opinion should be made clear in reporting, not buried to better support a theoretical end. In our case, students differed on the benefit of resource teams in the Flow Vis course. Some reported that their teammates were helpful, and that everyone on the team accomplished more as a result; others recounted that helping their teammates restricted what they wanted

to do. Far from hiding these tensions, we believe finding these contradictions can be the most fruitful area of development to improve a course (Tatar, 2007).

Pragmatic validation, the fourth facet of Q3, “concerns the compatibility of theoretical constructs with empirical reality” (Walther & Sochacka, 2014). Here, we are verifying that any new constructs generated still make sense in the “real world.” We are not generating new constructs, but moving them into a new situation. In prior research, TE has primarily been used in middle and high school science classrooms (Pugh, 2004). Thus far, our use of TE in engineering education research has been well-received by other engineering educators (presented at the Rocky Mountain Regional ASEE meeting, 2014, receiving best presentation). We also confirmed the applicability of TE with the main proponent of that construct (K. Pugh, personal communication 15 Jul 2014, 9 Jun 2015), who shared that TE was already being applied in some studies of undergraduate science (Heddy & Sinatra, 2013). Moreover, the TE is a practical theoretical framework in our research because it helps us describe observations, namely the unsolicited comments from students about “seeing fluids all the time.” We feel comfortable, then, to extend its use to undergraduate engineering education.

Ethical validation examines whether our integrity and responsibilities as researchers have been upheld throughout our studies, and asks questions such as “what are the impacts of our interests, biases, preconceptions, or intentions on this investigation?” (Walther & Sochacka, 2014). While we are closely linked to the courses we study, we also made efforts to separate research roles from teaching roles. The interviewer / researcher, a graduate student, was not an instructor or teaching assistant for any of the courses. The professor did not handle any research data with students identified, particularly before a course ended, a measure taken to avoid bias in both grading and research. Students were alerted to this fact before they participated in survey and interviews. Also, we have taken care to not discount evidence that challenged our particular hopes for these studies. For instance, we discuss student perception of Flow Vis being “an easy A,” a label that bothers most educators. Our intent was to understand the course

experiences as they exist, rather than examine a particular intervention, and discover those fruitful areas of contradiction.

The final facet of the Q3 framework shifts from types of validation to *process reliability*. This facet asks whether we can document the dependability of our process. Were we consistent in “our process of interpretation” and did we mitigate “random influences on our process” (Walther & Sochacka, 2014)? There are specific limitations to our data collection. For instance, the interview sample size is small (n=17). However, our average of four students per class gives us a small but relevant set of perspectives. In addition, the process included interviewing each subject twice, both at the beginning and end of the course. By gathering student feedback from these two points in time, we could better identify themes which held steady over the semester and those which changed significantly. In the area of data analysis, we engaged a second coder to review a sample of the interview data, to create a more reliable system of coding for our interview data. Also, our analysis of the survey data guided the examination of the interview data. The surveys provided broader coverage of each course, in a way that was less intrusive and a smaller time commitment for the participants.

In this review of the six facets of the Q3 framework, we find evidence for the validity and reliability of the interpretive portions of our work. We acknowledge the limitations of this study, and believe this is a well-grounded starting point for broader exploration of the transformative experience in engineering education.

Chapter 6 – Findings from Interpretive Research

This chapter presents the findings from our two interpretive lines of inquiry. (1) investigating the connections between two of the qualities of the transformative experience, student affect and expansion of perception, in the context of two fluids courses, and (2) the relationship between certain teaching methods and the transformative experience.

We begin with the survey findings for the fluids courses, Flow Visualization and Fluid Mechanics. This is followed by discussion of those results together with analysis of emergent themes from interviews and open response survey questions. This discussion traces several unexpected findings, including the relationship between the students' environment (in this case the Engineering Center itself) and their affective response to Flow Vis; open-ended assignments as a source of motivation; an interaction between grading schema and motivation; and an association between expanded perception and engineering identity.

We then discuss survey results from the Aesthetics of Design course, along with a detailed exploration of open response and interview findings. To organize those findings, we use a structure called a conjecture map (Sandoval, 2014) that highlights the connections between teaching methods, students actions, and learning outcomes.

The chapter concludes by drawing together the findings from these two lines of inquiry.

Expanded Perception and Student Affect in Fluids Courses

This section focuses on the student affect, the first of our three lines of inquiry, *in the context of a specific engineering domain, what is the relationship between student affect and a concurrent expansion of perception?*

We consider how students feel about the specific engineering domain of fluids by asking questions about their desire to study it, and their beliefs about whether it is useful to society or to themselves as engineers.

From these and similar questions, we gain a sense of what about fluids is interesting to students. We recognize that interest and positive affect are not synonymous. After all, a person afraid of heights would be very interested in learning about the strength of the safety railings around a balcony she must stand on, and this interest would not stem from positive affect. Similarly, students can express interest in a topic for the sake of getting a good grade in the course. However, for our purposes, we sought to gauge student interest as a means to understanding sources of positive affect related to the topic.

We begin by examining the numerically scored (closed response) items in the Fluid Perception (FluPer) survey, and then reporting the findings generated by examining both the interview data and the open response items.

Survey findings for Flow Vis and Fluid Mechanics

In the interests of combating the so-called decline effect (Lehrer, 2010; Schooler, 2011), we report the findings from all survey questions for both Flow Vis and Fluid Mechanics, despite few significant outcomes. On many questions, the Flow Vis students shifted very little in their responses from the beginning to the end of the course, and in a few cases significantly decreased in agreement. For instance for the Fall 2014 semester, the statement “I want to study fluids” resulted in a statistically significant *decrease* in agreement, for both the collective Flow Vis students ($p=0.001$) and for the Flow Vis engineering students only (the art/film student responses removed) ($p=0.003$). Other statistically significant shifts toward disagreement are denoted by ▼ in Table 6.1, with the positive shifts in agreement denoted by ▲. Parallel results for Fluid Mechanics are shown in Table 6.2. Refer to Table 5.1 for the full text of these questions. While the p value is used to determine statistical significance, the z -score in Wilcoxon Signed Ranks test is a convenient way to see direction of a shift. Negative z -scores are shifts toward disagreement. Positive z -scores indicate a shift toward agreement.

Wilcoxon Signed Ranks Test – Flow Visualization								
Course (n) (year)	FV - all (33) (2013)		FV- eng only (30) (2013)		FV – all (31) (2014)		FV- eng only (26) (2014)	
	<i>p</i>	<i>z</i>	<i>p</i>	<i>z</i>	<i>p</i>	<i>z</i>	<i>p</i>	<i>z</i>
Q6.1 (I want to study)	▼0.038	-2.074	▼0.069	-1.821	▼0.001	-3.234	▼0.003	-2.968
Q6.2 (useful to society)	0.593	-0.535	0.782	-0.277	0.285	-1.069	0.166	-1.387
Q6.3 (useful to me)	0.416	-0.814	0.397	-0.847	▼0.021	-2.309	▼0.021	-2.309
Q6.4 (I can study)	0.285	1.069	0.405	0.832	0.052	-1.941	▼0.021	-2.309
Q6.5 (difficult course)	▼0.026	-2.226	▼0.050	-1.964	▼0.003	-2.966	▼0.013	-2.473
Q6.6 (fun course)	0.305	-1.027	▼0.020	-2.333	0.166	-1.387	0.527	-0.632
Q8 (Fluids - interesting)	1.000	0.000	1.000	0.000	0.405	-0.832	0.206	-1.265
Q9 (Visualizations beautiful)	1.000	0.000	1.000	0.000	0.739	0.333	0.705	0.378
Q10 (Visualizations - fun)	0.405	0.832	1.000	0.000	1.000	0.000	1.000	0.000
Q13 (how often)	▲0.001	3.331	▲0.002	3.082	▲0.035	2.112	0.073	1.793

Table 6.1: Flow Vis (FV) Survey results for Spring 2013 and Spring 2014.

Results are shown for all students and for engineering majors only... Note: $p < 0.05$ indicates statistical significance. ▼ denotes a significant shift toward disagreement with the statement, and ▲ denotes a significant shift toward agreement with the statement. See Table 5.1 for complete questions.

Ceiling Effects Influenced by the Walls

The original validation of the FluPer survey had several significant results (Hertzberg et al., 2012), most of which demonstrated a shift toward agreement on many questions for the Flow Vis students, and often toward disagreement for the Fluid Mechanics students. Two other courses used as comparisons had

Wilcoxon Signed Ranks Test – Fluid Mechanics				
Course (n) (year)	FM (26) (2013)		FM (55) (2014)	
	<i>p</i>	<i>z</i>	<i>p</i>	<i>z</i>
Q6.1 (I want to study)	▼0.019	-2.351	0.857	0.181
Q6.2 (useful to society)	1.000	0.000	1.000	0.000
Q6.3 (useful to me)	0.558	-0.586	0.167	-1.38
Q6.4 (I can study)	0.356	-0.924	0.873	-0.16
Q6.5 (difficult course)	0.499	0.677	0.961	-0.049
Q6.6 (fun course)	0.248	1.154	0.100	1.646
Q8 (Fluids - interesting)	0.963	0.046	0.163	1.394
Q9 (Visualizations -beautiful)	0.377	-0.883	▲ 0.033	2.129
Q10 (Visualizations - fun)	▼0.023	-2.265	▲ 0.037	2.091
Q13 (how often)	0.224	1.216	▲ 0.001	3.346

Table 6.2: Fluid Mechanics (FM) survey results for Fall 2013 and Spring 2014.

Note: $p < 0.05$ indicates statistical significance. ▼ denotes a significant shift toward disagreement with the statement, and ▲ denotes a significant shift toward agreement with the statement. See Table 5.3 for complete text of questions.

mostly neutral results – little shift in either direction. A brief review of education-based interest survey literature reveals that often student interest in a topic remains neutral or declines over the course of a semester²⁸.

This general finding makes the 2012 results of the FluPer survey that much more remarkable, as it demonstrated that Flow Vis students actually increased their interest in the content of the course. This was gauged with questions such as “I want to study fluids”, and “The study of fluids is useful to me, as an engineer.” The 2012 study found that Flow Vis students, on average, had higher agreement with these statements by the end of the semester. At the same time, Fluid Mechanics students shifted their attitudes toward disagreement for these same statements (Hertzberg et al., 2012).

In our two semesters’ worth of responses, we were particularly interested in where Fluid Mechanics students shifted toward agreement. In contrast to the 2012 findings, we found in 2014 that the Fluid Mechanics students had significant shifts toward agreement for three statements:

- Visualizations of fluid flows are beautiful
- Visualizations of fluid flows are fun
- How often do you both notice and think about fluid flows outside of the classroom?

All three of these statements relate to the appearance of fluid flows, either the visualizations themselves or to the students’ increased awareness of the flows. Only for this last question did Flow Vis students also have a positive shift, both as an entire class (in both 2013 and 2014), and for the engineers only (in 2013). The difference was not statistically significant for the 2014 class when only engineering students were considered. There are a number of explanations we could develop for these changes from

²⁸ Some measures of interest have found that interest decreases most for high-achieving students while middle and low achieving students remain neutral or even increase interest (Frenzel, Goetz, Pekrun, & Watt, 2010). Another study divided “task value,” or the worth a student assigns to the content of the course, from student interest in the course, and found that task value declined even when reported interest remained the same (Zusho, Pintrich, & Coppola, 2003).

the original 2012 results. Perhaps the students from those three and a half years (Fall 2008 - Fall 2011), were anomalous, and we have simply reverted to the interest-waning effects reported by others.

Another possible explanation may be that student expectations for Flow Vis have changed. For instance, the median response on the precourse survey for Flow Vis students was the highest level of agreement (a '1') on the survey, for most of the numerically scored questions. Only two questions did not "hit the ceiling" in this manner. They were Q6.5 "I expect this to be a difficult course," and the question asking how often students notice and think about fluids (Q13). This last question (how often students notice fluids) is central to the Fluid Perception construct, and in fact, the only question where Flow Vis students still increased their agreement significantly. On the other hand, we now view the question about course difficulty as tangential to the central construct of Fluids Perception, and the question is being reassessed. Interestingly, that the original FluPer survey study did not show this degree of ceiling effect, an indication that students' expectations for the class have likely changed since those years.

These high expectations for Flow Vis have probably been fueled by hearing about the course from past students and by visual cues. The Engineering Center's lobby and classroom wing now feature more than 25 nicely framed, poster-size images of fluid flows²⁹. On one stretch of wall covered in these images, there is also a smaller sign describing the course and pointing out that the images are all student work. In addition, there is a display of more student flow visualizations in the lobby / coffee shop area of the Jennie Smoly Caruthers Biotech Building, the main engineering building on the newer east campus of the University of Colorado Boulder. Other studies have found that environmental cues like these do influence students (Cheryan, Plaut, Davies, & Steele, 2009). The halls students walk everyday now feature Flow Visualizations at every turn: the very walls are an influence. This flow vis rich environment may influence the Fluid Mechanics students on the visually-oriented questions, which most recently had positive shifts. That same environment is part of what is generating a high initial interest for Flow Vis

²⁹ A set of smaller flow visualizations was hung in the Mechanical Engineering hallway in 2006. The images highlighted here were hung in more central areas, the Classroom Wing and lobby, during Fall 2013.

students. This becomes an even more plausible explanation for the ceiling effect in the survey data when we cross-reference interview responses:

I have heard awesome stuff about [Flow Vis] all four years I have been here. I had an excitement factor first of all.

– FVESub01, int 1³⁰

The first time I heard about [Flow Vis] was looking at the posters on the walls and seeing that and thinking, making pictures for class? That's awesome. That gives you mechanical engineering credit?

– FVESub09 int 1

Even students who did not connect the posters to the course before enrolling in Flow Vis expressed more motivation after learning that they were:

I didn't know that all the artwork in the engineering center was actually Flow Vis artwork from students. When I went into the class I was thinking oh wow, I am going to learn to develop something that insane.

– FVESub03 int 1

In contrast, Fluid Mechanics is often a course students take only because it is required. Two of our four Fluid Mechanics interview participants indicated they had no real expectations for Fluid Mechanics; it was merely next on the list they had to take. This is echoed by pre-course Fluid Mechanics responses to Q16 (What do you think and feel about fluids”), which included “something I have to study to graduate” and “they're important but I don't feel anything about them.” One interviewee shared the faint praise “usually what I hear about class is that it is bad. I didn't hear much about this class which is good.” (FMSub11 int 1). In some cases, the expectations for Fluid Mechanics are tinged with dread. A few students expressed a “nervous but excited” (FM13Sub21) sentiment in the precourse survey. One candid respondent even wrote “I am terrified” (FM14Sub47). Our third interviewee gave a more nuanced description of Fluid Mechanics' reputation:

³⁰ Subjects abbreviations: FVE – Flow Vis Engineering Student; FVA – Flow Vis Art Student; FM – Fluid Mechanics Student; AD – Aesthetics of Design Student. First or second interview are marked as int 1 and int 2. Survey respondents also have a year indication (13 or 14). Survey respondents were numbered separately by semester, such that FM13Sub09 is not the same student as FM14Sub09. See Appendix A for full explanation of subject identifiers.

I used to think [Fluid Mechanics] was supposed to be this really hard class. **So I was just kind of scared of the hard fluid mechanics class I'll have to take some day.** [Now] I'm finding it to be hard-ish. Some kids love it. I was talking to one girl who said 'I love it, it was my favorite class! It was so fun!' And then another kid said 'I hated it.' He'd had to try it twice.

– FMSub04 int 1, emphasis added.

Fluid Mechanics' reputation as "this really hard class" may lessen over the course of the semester as it is demystified through familiarity. However, there are contradicting results between the 2013 and 2014 surveys on this point. For Q6.5: "This is a difficult course" the two semesters shift in opposite directions, with neither result significant. For Q6.6: "This is a fun course," both semesters of Fluid Mechanics student shifted toward agreement, which at $p = 0.10$ for 2014, was not significant, but noteworthy. More encouraging is the shift toward noticing fluids more often (Q13). Both Fluid Mechanics semesters showed a trend toward noticing fluids more often, and the 2014 results were statistically significant. This specific finding matches the 2012 FluPer study, where they reported the only positive shift for Fluid Mechanics was also on this one question. This makes us ask whether Fluid Mechanics students are experiencing a Twain-like expansion of perception, critical and affectively negative.

Four Categories of Interest Revealed Through the Survey

To gauge whether noticing fluids more was associated with positive or negative affect, we went through the open responses to the survey. Here we identified four main sources of interest for working with fluids, reasons students gave when asked Q7 "What do you think is interesting about fluids?" Many of these sources of interest also came up during the interviews.

- Complexity or Difficulty
- Application or Uses
- Ubiquity
- Aesthetics

In Table 6.3, we show percentages of responses for pre and post surveys, shown as pre% / post%. Sometimes responses contained multiple reasons, thus pre/post percentages may not total 100%. For vague responses, such as “everything” we counted the response as “other.” Some students, particularly on the post surveys, responded to only the numerical portion of the survey, leaving this question blank.

Course (n)	Complexity	Applicable	Ubiquity	Aesthetics	Other	None
FM 2013 (26)	58% / 23%	4% / 27%	12% / 8%	8% / 8%	8% / 0%	12% / 35%
FM 2014 (55)	31% / 24%	27% / 33%	22% / 18%	13% / 7%	4% / 13%	16% / 15%
FV 2013 (33)	55% / 52%	18% / 9%	18% / 6%	27% / 30%	6% / 6%	12% / 21%
FV 2014 (31)	65% / 61%	16% / 6%	13% / 23%	13% / 13%	0% / 0%	6% / 13%

Table 6.3 Responses grouped by the four main reasons fluids are “interesting.”

For pre/post surveys, Q7. Some responses contained multiple reasons; percentages may not total 100%.

Complexity

The primary source of interest students cited was the challenge of fluids’ complexity. Some students expressed this as mystery or mentioned the difficulty of predicting fluids behavior. “The fact that they are so chaotic” (FM13Sub08) and “The odd way they behave in certain situations, unpredictable” (FM14Sub11) were common reactions. Other times, the apparent simplicity of fluids was contrasted to their underlying complexity:

How fluids respond to situations seems very intuitive, but the reasons why they do can be very complex.

–FM13Sub04

A few students highlighted the challenge of fluids’ complexity as motivating, “They’re understood by few and honestly I like knowing things other people don’t” (FM13Sub13). Complexity also tended to intersect with comments about how “cool” images looked and other indications of aesthetic response: “Their behavior when forces are applied to them. The formations that are created can be very amazing visually” (FV13Sub24).

Applicability

The second source of interest was the broad applicability of fluids. Some students listed specific uses of the course material, “They represent many real world energy issues” (FM13Sub08), but more simply

commented on the many practical uses of what they were learning: “All of the applications. It isn't just about water in pipes” (FM14Sub52).

The Fluid Mechanics course assigns problem sets written by the professor, not from a textbook. One interviewee identified this as helping students see the applications of fluids more clearly:

The way that she makes us think about it in real life. We have to make our own assumptions. We have to just kind of **make the problem our own problem** rather than have really strict guidelines like a book problem would.

–FMSub11 int 2, emphasis added

One Flow Vis engineering student found the practicality of fluids to be influenced by the aesthetic qualities. Here, the two types of interest in the subject of fluids are additive:

Fluids has the potential to be both aesthetically beautiful and useful to society. I have found that often times, **studying the beautiful aspects of fluids has the potential to be extremely useful** to society, such as in jet propulsion.

–FVE13Sub17, emphasis added

Another commented that understanding the broad applications of fluids encouraged them to persist in the course: “They're tremendously useful, even if they get complex” (FM14Sub20). In this way, we see how having one particular interest can help overcome challenges.

Ubiquity

The third interest noted was the ubiquity of fluids. This was expressed differently than appreciating the myriad uses of fluids; it was more an awareness of how much we are surrounded by fluids. It was often in pithy phrases such as “all around us” (FM14Sub29) and “We live in them” (FM13Sub16). One student expanded this a bit:

The most interesting thing about fluids is that it is everywhere around us in daily life, something that I was not so aware of before taking this course.

–FM14Sub24

Ubiquity also came up as students mentioned whether their intuitions worked for or against them when trying to understand fluids problems:

Once we suffered through the math of it all, I liked that fluid flow actually makes sense. It is found in all parts of our lives and suddenly it all makes sense

–FM13Sub09

This type of interest seems to extend most naturally to the expansion of perception of the transformative experience. Although impossible to glean from the survey responses, it seems likely that indeed, this student had a transformative experience, because in response to Q15 (Do you feel you can describe the physics of fluids that you encounter? Do you ever want to?), the same student responded, “Yes, I have to restrain myself from explaining to those around me how cool the physics is” (FM13Sub09).

Aesthetics

The fourth reason for interest in fluids identified from the survey was the aesthetic qualities. This included noting fluid flows’ beauty, or simply that “they look really cool” (FM14Sub30). As we noted under *Complexity*, aesthetic appeal was often mentioned with complexity:

They are beautiful in their very nature. Their exact state of motion may never be exactly replicated... one of a kind.

–FM13Sub15

Flow images can be classified by their appeal to a “power aesthetic” or “an aesthetic of destruction” in addition to the more soothing types of beauty associated with laminar flows. We were pleased to find any reference to aesthetics in the Fluid Mechanics data, while we anticipated higher occurrences among the Flow Vis students.

One student, in the short space allotted on the survey, nearly managed to express all four types of interest in fluids in one response:

Its relevance is very interesting, because it is part of everything. Everywhere one can look has fluids involved. Fluids is also beautiful, especially when it is understood why it behaves a certain way. Most of all, fluids’ reaction to varying forces is also interesting.

–FVE13Sub24

Everything and *everywhere* denote ubiquity, *beautiful* indicates aesthetics, and *reaction to varying forces* speaks to complexity. Taken one way, *relevance* might even cue application. Perhaps more importantly, the student claims fluids are beautiful especially when the science behind them is understood. This places the student firmly in Feynman's camp (Feynman, 1988), and has likely had a transformative experience.

We believe fueling multiple interests for students is a good approach, because interests will wax and wane during the semester, during their time in school, and indeed throughout their lives. Some students may find that particular interests may aid or increase other interests, as in the case of FVE13Sub17 who found that the beauty of fluids enhanced the understanding of fluids applications. In other cases, we find that some particular interests can help students sustain their efforts through the challenges. If we only seek to use one or two of the four interests listed here (and there are others³¹), we have severely limited our ability to encourage and engage students.

Affective Response

You must be shapeless, formless, like fluids. When you pour fluid in a cup, it becomes the cup. When you pour fluid in a bottle, it becomes the bottle. When you pour fluid in a teapot, it becomes the teapot. Fluid can drip and it can crash. Become like fluid my friend. (FM14Sub37)

We are encouraged by the different reasons students found for their interest in fluids, especially ubiquity, since it is related to expanded perception of the transformative experience. However, we found in Fluid Mechanics that this was not necessarily associated with positive affect. To probe that connection, we turned to the last question of the survey, Q16, "What do you think and feel about fluids?"

By the last question of the survey, there were signs of survey fatigue, with glib answers including "I feel that fluids are complicated. I think that fluids are complicated. I know that fluids are complicated" (FM14Sub37), "I'm pretty liquid on that subject" (FM13Sub14), and "generally wet, the best one is beer"

³¹ Studies of socially engaged engineers, including Engineers Without Borders, found that serving society's needs is also a source of motivation for many (K. I. Litchfield, 2014; K. Litchfield & Javernick-Will, 2013).

(FV13Sub30). These comments might also be read as resistance to sharing affective reactions to the course, as demonstrated by the respondent who compared the survey to a matchmaking website:

This is starting to resemble what I could only imagine an E-Harmony interview looks like. That being said I think fluids are pretty interesting.

–FM14Sub17

Many answers were more forthright, and we see percentages for positive and negative affect from Q16 in Table 6.4. Glib answers were counted as neutral. Comments such as “they’re important” (FM14Sub20) that did not indicate an affective response were also coded as neutral.

Course (n)	Positive	Negative	Neutral	None
FM 2013 (26)	54% / 50%	4% / 0%	12% / 12%	31% / 31%
FM 2014 (55)	38% / 62%	4% / 4%	35% / 15%	24% / 20%
FV 2013 (33)	73% / 64%	0% / 0%	21% / 21%	6% / 15%
FV 2014 (31)	68% / 68%	0% / 0%	16% / 19%	16% / 13%

Table 6.4 Pre/Post Courses Survey Affective Responses
 Totaled as percentages, for Q16 “What do you think and feel about fluids?”

Given the social desirability bias, we expect that blank and neutral answers are masking negative responses to the course and / or to the topic of fluids. Consider how carefully this student avoided saying anything negative about fluids as a topic:

I think that fluids are an essential part of our everyday lives, and the study of them is critical to understanding the world around us. The photography of fluids is a unique art, and I have enjoyed learning about photography.

–FV14Sub06

So, in general we see students’ affective responses to fluids do not change for either course. Flow Vis students both begin and end the semester with a higher affective value for fluids. A large part of the differences between Flow Vis and Fluid Mechanics may arise from the “elective effect”, a term coined by the researchers in the original FluPer survey study (Hertzberg et al., 2012). Elective effect captures the idea that students tend to exhibit more positive affect whenever the course is elective, rather than required. Students likely chose Flow Vis because they are interested, although scheduling conflicts and other factors also influence their choices. It is logical, then, that students would express more interest in

something they have chosen over what has been dictated to them. This is in line with Self-Determination Theory, which states that a sense of autonomy is motivating (Deci & Ryan, 2008b). An extension of this idea is the reaction students have to the open-ended assignments in Flow Vis.

Motivation through Open-Ended Assignments

I liked the freedom... there was no, 'oh no you have to have at least three colors in your photograph.' There was no distinct 'this is your rubric.'

Interviewer: no, you'd better be capturing this phenomenon?

Exactly.

–FVESub03 int 2

One feature of Flow Vis that makes it different from most engineering courses is the nature of the assignments. Each of the six assignments requires an image or video of a fluid phenomenon, followed by a written explanation of the image. Two are of clouds, but for the remaining four assignments, there are no restrictions on what kind of fluid flows the students should capture. Conversely, typical engineering courses include problem sets and small projects, all with set expectations for output. As one Flow Vis interview participant phrased it, "Usually the classes are all the same. You go to lecture, you learn a new formula or you learn a new concept. And then you practice it" (FVE Sub03 int 1).

Even the design courses, which feature larger projects and more than one solution to the task, have detailed scope and highly structured requirements listed for the final products, and projects are typically graded according to a fixed rubric.

[Flow Vis] is more similar to projects classes but it was so much more creative and up to you.

–FVE Sub01 int 2

The advantage of the open-ended assignments is precisely what this student notes – the creativity and flexibility, which many of the students observe is highly motivating:

Whereas Flow Vis, it's really up to your imagination as to what you want to do. You have more freedom in what area you wish to pursue... as opposed to – alright, this is the first thing you learn, this is unit one, this is unit two. There's not set units. It's just a **continuous application of your imagination with some honing along the way.**

–FVE Sub03 int 1, emphasis added

As students progress through their undergraduate education, a balance of open-ended and highly structured assignments is desirable (Schwartz, Bransford, & Sears, 2005). Sometimes, being given structured expectations for their work is exactly what students want and need. Several Fluid Mechanics students commented that they appreciated the required structure for the assignments. Consider this exchange during an early course interview:

[Fluid Mechanics is] focusing a lot on critical thinking, and problem-solving techniques. Really **focused on a getting good clear problem statement, getting a good clear list of givens** and I think that's really important, but it isn't always focused on in every class.

Interviewer: You like that?

Yeah, I do like that. It's helped me get better scores in other classes' homework. It also helps me take a step back and look at the entire picture of the whole problem. And really think, "is this a reasonable solution?" That's a big part of it. I had not done that as much.

I always checked my answer in my head, but I've never written a statement about it.

And writing a statement about it really helps your reader see the limitations of it and not just take it as fact. So that you can say oh, I see there are limitations, and look the author even mentions them. I hadn't even thought about that before.

–FMSub04 int 1 emphasis added

That same student reported at the end of the semester:

[Fluid Mechanics] was a lot of focus on the problem solving method. It really did beat into my head the steps. Take these steps, use them every time, and you'll have good success. So I think that part was really helpful.

–FMSub04 int 2

Another Fluid Mechanics student remarked:

[The professor] spent an entire lecture of 'this is how I want your homework laid out, this is the process you go through and you can apply it to other places and these are the basic sections that you need... which is good because then you know what the expectations are. If you are looking at somebody else's work ...you know where you are going to find certain information.

–FMSub08 int 2

A third Fluid Mechanics student offered this insight on homework, from his experience as both a musician and an engineering student:

The act of practicing, trying to get better at something, is another overlap with [music and] engineering. You have to do it; it's not really studying. **To me studying for engineering is more practicing** and practicing problems.

–FMSub11 int 1, emphasis added

Yet, the assignments in Fluid Mechanics have more flexibility designed into them than those in many other courses. Described in Chapter 4, the Fluid Mechanics course syllabus requires students to locate a recent fluid mechanics textbook, but no specific text is required. Instead, students are expected to locate the chapter relevant to the section they are learning in lecture, and gain the additional perspective provided by seeing the material described in another way. Problem sets are written by the professor, not from a specific text. This is done in part to minimize cheating, which occurs more readily when students can simply buy the instructor manual online for a specific text. Another reason for the customized problem sets is it allows the professor to build in more relevant problems. Two Fluid Mechanics interview participants favorably mentioned a specific problem involving a fountain outside a wing of the Engineering Center as different from their other engineering homework experiences.

I like the way that [the professor] makes us think about it in real life.... We did a problem about the fluid mechanics of the globe [fountain] out here. We had to make assumptions on the size of it. She told us the material it is made out of so we had to go online and look up the density. We're not exactly spoon-fed all the information.

–FMSub11 int 2

Putting the content in a “real life” context motivates this student, and the requirement that they search for the information they needed to solve the problem was good, but also annoying. Later in the same interview:

Some of that makes it good, some of it goes a little too deep and doesn't really help. Like some of the stuff that we have to look up online or some of the stuff that we have to assume about, I don't find always extremely helpful, but in general, that concept of do your own research for this problem, helps, while some of it can kind of be annoying.

Interviewer: Do you think that's maybe part of what engineers end up doing on the job?

I think so. And I think that's kind of the point she is trying to make in the way she writes the problems.

–FMSub11 int 2

We are not suggesting that structured assignments are bad, only that the opportunity for some self-directed learning is beneficial. As this Fluid Mechanics course demonstrates, there are levels of structure possible between fully specified problem sets and completely unspecified challenges. Open-ended assignments are appropriate for upper class students, who are typically ready to synthesize material from multiple foundational courses. However, open-ended problems do not reduce the amount of planning required of students. In fact, in some ways Flow Vis assignments require more preparation:

I wasn't expecting [that] when you do the projects you do actually have to do some degree of planning. **It gave me more of a feeling that I'm trying to solve a real engineering problem** instead of just going straight into it assuming that oh, you'll probably use some of this information [taught in class today], it's up to you to re-solve it. Instead take it one step at a time. Sort of plan out your process before you go straight to it.

–FVESub03 int 2, emphasis added

The necessary planning did not reduce the flexibility of the work. One student described how her team coordinated to video mixing honey and dyed corn syrup. They filmed the two fluids mixing as planned, and then “one guy said, hold on, I just want to do the honey alone and do some close-up pictures of it, not a video, and those turned out amazing” (FVASub06 int 2). The flexibility of the assignments allows for students to explore such unexpected inspirations. Even mistakes can be useful. As one of the art students put it:

Everything is an experiment so as long as you try something, you did good. You don't have to worry. If you mess up, make a thing out of what you messed up on. ...I kind of liked how the messed up image looked, **so then I wrote in the paper about the physics of why it messed up.**

–FVASub05 int 2, emphasis added

This attitude of learning from the “mess ups” as well as the planned flows is beneficial. After all, the practice of engineering is as much about understanding what happens when things do not go right as when they do. In addition, learning from mistakes is a hallmark of a growth mindset (Dweck, 2007). This connection between motivation and the openness of assignments came up again in the Aesthetics of Design course. Part of our purpose in mimicking the open-ended assignments from Flow Vis in Aes Des was to cultivate precisely this sense of free-flowing creativity and ensuing motivation that students exhibited.

Yet, what does the student mean in this last quotation when he says, “you don't have to worry”? He is indicating that the flexible assignment had an equally flexible grading system, a system to which students reacted both positively and negatively.

Grading and Flow Vis

And then I met someone that took [Flow Vis]. I asked him what it was like and he said it's really as easy as you make it. That's not why I'm taking it; I'm putting more time into this class than anything because I like it. But yeah he said it's really cool, it's just what you put in is what you get out.

–FVESub09 int 1

“You get out of it what you put into it,” and “it's as easy as you make it,” are true of many classes, but this student was hinting at Flow Vis's reputation as an “easy A”. Due to effects like the social desirability bias, which is the tendency of subjects to alter their responses to align with social norms, we realized we probably would not be able to detect from interviews or surveys students who take Flow Vis primarily for this outcome. Observe how this student interjects, “That's not why I'm taking it.” Students want to avoid being viewed as uncommitted. Flow Vis's reputation is not inaccurate. As mentioned in the course description, any student who fully participates receives an A in the course, and very few receive a grade other than an A.

This grading policy reduces the amount of pressure to be correct on assignments, allowing more creativity, more of a “zig zag” process (K. Sawyer, 2013). Students do not need to worry about the grade while creating and capturing their images; if they are creating images and writing the papers, they receive an A. Some students respond positively to this policy:

[Flow Vis] was one of the classes that actually took the edge off of engineering because senior year is a little stressful. It really, really helped even it out.

–FVESub03 int 2

This particular subject also expressed becoming engrossed in the post-processing of the images, and gaining a deeper aesthetic appreciation of fluids. We see that pressures other than grades can be effective.

Part of this stems from the professor’s attitude from day one:

I am very impressed by first of all, [the professor’s] professionalism. She is very serious about something that it is very cool and exciting... It makes kids take it much more seriously... And it shows in the work. Kids for the first projects were doing really, really cool stuff.

–FVASub07 int 1

Public presentation compelled students to create better images and video as well. Students looked forward to presenting their work in class, but several also commented on valuing other audiences. For example, Subject 9, an engineer, mentioned that family members were artists and a close friend was a film major. He made his images with the intent of sharing them with these important people in his life.

This provided far more incentive than points toward a grade:

I took more pride in [my Flow Vis work]. Just because I didn’t feel that any of it was, pardon my language, absolute bullshit. I feel at times [professors] assign work because they have to; we need it for grades or something. [In Flow Vis] you were actually doing something.

–FVESub09 int 2

Others commented on “really making something” or having a final product (the image with the corresponding paper) all their own. Even with these other, more personal incentives, some students missed the validation of grades:

Interviewer: What was useless about this class?

I felt that the papers being ungraded...

Interviewer: So doing the papers wasn't useless?

No, I like doing the papers. He [the TA] gave very constructive good feedback but....

Interviewer: ...I would like to know if this would be an A?

Yeah, I just felt zero motivation to work hard on the papers because I knew...

Interviewer: ... She is not going to assign a grade to this.

Yeah. I guess it's great, because it's like boom, A.

Interviewer: Do you feel like an A means less in this class because you don't feel like you had to work as hard for it?

Yeah. [pause] I like the images not being graded. I don't know how you would grade that.

Interviewer: Right, because the artistic range of this class is just all over the map.

And I know that there's different expectations for the papers for the different people in the class so I'm not sure ...

Interviewer: What would be a good standard?

Yeah. And I think she should put in an attendance percentage because I feel like there was a lot of...

Interviewer: slackers?

Yeah. I mean only if it's like a small percentage, there should be a grade

Interviewer: ...a blip, because you showed up?

[Participant nods]

–FVESub01 int 2

In addition to the lack of specific grades on the papers, this student was also frustrated by classmates who appeared to put in minimal effort. Subject 1 was hesitant to voice her annoyance and clearly did not want to criticize either the professor or her classmates. Her feelings align with the regulatory fit model of motivation, where we find that people can be intrinsically motivated, provided they view their extrinsic rewards as appropriate, in context with the efforts of other people doing similar work (Higgins, 2012). In this case, the subject finds grades do not “fit.” She is demotivated because she sees others receiving the same reward for less effort. She would like a small portion of the grade to reflect attendance, as a mark of a student's seriousness. Another student, also annoyed by the lack of seriousness, suggested a different solution:

So once we started doing the team projects, I could not focus as much on my own photography and I was trying to help everyone else more....There was a kid in my group who wasn't [taking it seriously]. Not at all... I think [a screening process] would be beneficial, rather than first come first serve. [Ask them] do you care? ... Or maybe group the more serious students all together, and the less serious students altogether.

–FVesub09 int 2

For this student, his teammates' lack of seriousness detracted from his own work. His last suggestion, to place the more passionate students together, is something the professor already attempts to do when creating the teams, by asking how much time or effort students intend to put into the course each week. However, we suspect that social desirability bias, or perhaps simple wishful thinking, compels students to assert that they will be more committed to the course than they eventually are.

This is an area requiring more thought. Too lax a grading scheme appears to demotivate the students who genuinely engage with the work (Higgins, 2012), yet we know that too strict a grading scheme can dismantle the creative process (Pink, 2009). As we will see with the Aesthetics of Design course, a non-traditional grading scheme supports more risk taking, with many positive results.

Expansion of Perception and Engineering Identity

You find yourself thinking about things differently, you know. Like why did that pencil fracture, why is that river running the way it is. Just having that knowledge, you kind of begin to think and see things differently.

–FMSub10 int 2

An expansion of perception, or seeing the world through the lens of the content students are learning, is a primary motivation for our work. We had hoped to record reports of expanded perception, and gauge increases or decreases of expanded perception through those reports. One challenge we faced in this task is that the most salient examples of expanded perception are those that students offer without prompting. When asked on the survey, virtually all students could provide two examples of fluids in their daily lives. None of these responses seemed to signal the kind of shift of perception we were hoping to document. We focused on the interviews for signs that the transformative experience in fluids had occurred for at least a few of the students.

We were surprised to find, instead, that engineering students, in all of the courses we investigated, identified expanded perception as a function of their identity as engineering students. The first example is particularly notable as an early course interview of a Flow Vis engineering student. The episode he recounts is *before* he took the course:

Interviewer: Do you identify as an engineer?

Absolutely. About a year ago, I was up in Vail with some friends, and some friends who were not [in] engineering. They dropped a teabag and the dye start coming out [in the hot water], and a friend, who is an engineer, and I were talking about the flow physics and everybody else was completely saying, what are you guys talking about? It's just a teabag. ...I usually think of myself as an engineer, I see things through an engineering perspective, as opposed to whatever perspective they might have.

–FVESub03 int 1

The fluid mechanics students also expressed a view of life outside of the classroom influenced by their studies:

Yeah, I think [being an engineer] is the way you look at things... when I'm driving in my car I'm thinking about what I can't see, like how the engine is working, what is happening in the fuel tank. I think non-engineers wouldn't think that way. They trust that it works. They don't think about why or how.

–FMSub11 int 2

One Aesthetics of Design student shared that what made her an engineer was “my curiosity about how things work ... it's my thought process” (ADSub13). Another Aes Des student commented that he had only begun to feel like an engineer in the last year. When asked for an example of what had changed, he offered:

When we purchase a product for example, something in my daily life, I look at it, try to make sense of the price, how it was made, what kind of material it is. Even when I'm sitting in a building I look at the structure of the pipes, how they were put and all of these things I've never thought about before. Before I was like ‘oh, I just want to get a cool laptop’ but right now when I look at a laptop, I see how thin it is, what kind of technology must have been made into it, so all of these things come to mind.

–ADSub02

FMSub04, a Fluid Mechanics student coming back to college after a break of several years, shared this experience:

Interviewer: What does it mean to be an engineer?

Part of it is a whole different view on life. I see life as systems. I was up the other night and I saw the clouds, the steam coming off the energy plant, and at one in the morning it was really calm and the moon was up and you can see the column rise, and spread, and I was thinking from an environmental engineering aspect, how does that column spread over the distance, and from fluid mechanics, aw, look at the turbulence and look at the laminar flows. [My first time in school] I felt like I was getting that awareness of systems, and now it really is kind of embedded.

–FMSub04 int 1

This student assigns affective value to the experience (in the audio recording, there is an excited tone in his voice as he recounts the story,), and it is an aesthetic experience as well. The morning is “really calm and the moon was up” – he is enjoying the scene, and enjoying using his knowledge to discern why the steam and clouds are forming just this way. When asked if he felt this awareness had developed suddenly or gradually, he replied:

More gradual. It’s just sort of the way I see the world now. I was thinking about it the other day. So 10 or 15 years ago I used to just see cars. But now I see car makes and models, and new technology going on there. I remember when I first started working on cars I couldn’t tell a difference between a Jetta and a Passat until I looked at the badge. And now I look at it and definitely see that it’s a different model. It’s like that.

–FMSub04 int 1

Here we witness two aspects of the transformative experience: the experience of *expanded perception* clearly has *affective value* for these students. But it is also easy to see how this expansion of perception can be highly critical, a perspective oriented on judgement not unlike Twain’s view of the river (Twain, 1883):

So I’m in fluid dynamics this semester, so I have that lens on my life. Okay how do I see what I’m doing at the [machine] shop? Oh that’s why coolants are important in this aspect, or that’s how water is getting to my tap. For me it’s always, how does this work? Or why does this work? And I think that happens with any class, you know, when you’re in solid mechanics, you think why is this working, what stress is this going under, where is this most likely to fail?

–FMSub08 int 2

Later in the same interview, this Fluid Mechanics student explains how the Flow Vis of the Day is useful for how it helps her solve problems:

That's a nice textbook problem [sarcastic]; now let me go apply that in real life. To actually be able to see it applied was good... you see one [flow visualization] and then you can then take that and imagine it in other problems. This is what you can picture in your mind, instead of thinking 'well, this is what it's doing, but I couldn't really tell you', because you have a point to reference back to, it's a lot easier.

–FMSub08 int 2

Yet even this very application-focused student expressed positive affect for her work:

Being able to do those calculations makes me more aware of [fluids], because that's how my brain's wired: calculations and numbers and doing little steps in my head and seeing how things work. So to actually have the knowledge now behind that, to be able to analyze it, I do. Because that's what I do for fun.

–FMSub08 int 2

There is less a sense of wonder in FMSub08's words than there is pragmatic assertion. She wants to understand the tough concepts, she wants to use them, and she enjoys the mastery of knowing how things work. Productive as this focus on applicability is for her, there are moments when that is not enough for her to establish the strong conceptual understanding she wants:

You can sit there and tell me, this is the assumption you make here, this is the assumption you make here, but if I don't have a tangible grasp on what that assumption actually means...sweet, I'm going to write that down on my crib sheet [for the test].

–FMSub08 int 2

On the surface, this student may not sound that different from the earlier examples, who expressed similar curiosity about how things function. Yet, what is missing from her words is the flexibility, the willingness to wander a bit, the ability to zig-zag creatively. Her examples are work-focused, and there is no sense that she would play with fluids in order to learn more about them. We speculate whether she would benefit from developing more sources of interest in her coursework and beyond, and we wonder if a course like Flow Vis would help her find that motivation.

How Engineering and Art Students Benefit From Working Together

Another powerful way to examine our interview data is by comparing the two distinct groups within the Flow Vis course to each other: the engineering students and the art students. While we label all the

non-engineering students “art students,” they came from three different groups: fine arts photography, film, and technology, arts and media (TAM). In these comparisons, different trends became visible, both in the groups’ similarities as well as their differences.

From the early course interviews (labeled int 1), we observe that the engineering students found the combination of art and engineering to be motivating, both in the sense of blending disciplines and in the sense of working with art students:

I thought [Flow Vis] was going to be sweet, mixing art and engineering because I do love physics and talking about it conceptually is really cool.

–FVESub09 int 1

Mix with art students? How fun is that?

–FVSub01 int 1

Later in the same interview:

It’s so interesting to think about engineering concepts in ways engineers don’t think about them. Which is something this class does expertly well. Because we’re showing fluid dynamics to people who are looking at art.

–FVESub01 int 1

The art students found the idea of working with engineering and engineering students to be motivating as well:

I’m just excited to deal with the engineers, and see what kind of creative concepts we can come up with. It’s going to be cool.

–FVASub05 int1

I had been walking through the engineering center, and I had seen these pictures from Flow Vis... I looked it up, and I was able to take it. I didn’t really have that many expectations. I knew we were going to be doing some really cool science-slash-art, and that’s what really intrigued me the most was mixing the two.

–FVASub06 int 1

At the content level, engineering participants described using their fluids knowledge in new ways, even in early course interviews. We might call this scaffolded *motivated use* of the content. Scaffolded, because the use of content is assigned, not spontaneous, yet still in a new context:

Every single time we talk about photographic technique, or develop a flow product or a combustion project, those are all backed up with examples from the real world.... It's not just this is a problem from the book or 'ignore friction here'. All these things are real applications, all factors are considered.

–FVESub03 int 1

[Flow Vis] is like Fluids 2. Now that you know the basics, you can apply them to making cool artistic pictures.

–FVESub01 int 1

Later in the same interview:

I feel like [art students] are going into the dark trying to find art, and I am going in dark trying to take pictures of my ideas.

–FVESub01 int 1

This last quotation points again to the openness of the assignments, which was associated with a sense of exploration, instead of finding existing answers. This activity could be called exploring, or tinkering with ideas, and clearly resembles one type of motivated use. Students from both groups commented on this characteristic, mostly in their second interviews:

You can modify your pathway [in Flow Vis]. In math there's only one way, but in [Flow Vis] it was more along the lines of this experiment is how you choose to direct it.

–FVESub03 int 2

In Flow Vis, the end is so variable, that it was very dependent on the person.

–FVESub01 int 2

[In other courses] you create such a rigid thought process rather than a really flexible, dynamic space.

–FVESub09 int 1

[Experimental film] is such a lofty term and it's used a lot, [but] here we were truly experimenting, which is the most beautiful part about it. You are producing something through experiment.

–FVASub16 int 1

The same participant in his post course interview commented:

I love the open-endedness of pretty much everything in that class.

–FVASub16 int 2

I kept a notebook next to me during the critiques [to write down] any ideas that I wanted to try, not for the class but just because I thought they were cool and could make good images or for a different project that I'm doing, just in my spare time.

–FVASub06 int 2

This last comment, about using these ideas outside of the course, in unrelated projects or even just in her spare time, is a clear indicator of *motivated use*.

Among the art students, some identified as experimental film makers, and commented that capturing images such as the ones in Flow Vis are important for adding texture and evoking emotions in their work. One film student commented that he had learned as much about using his camera in the first two weeks of Flow Vis as he had in a whole semester of a photography course. This highlights the concentrated nature of the early sessions of the course, which enable students to begin finding and capturing flow images quickly. Getting to hands-on assignments swiftly may be worth replicating, as it supported the scaffolded motivated use of content.

While engineering students commented on the way Flow Vis showed them fluids content in a new context, the art students commented directly on *expanded perception*:

In terms of appreciating flows and keeping a keen eye out for it, that's totally improved drastically... I don't want to make another film without including one flow vis.

–FVASub07 int 2

I learned to investigate texturally ... It's right under your nose, bubbles in the dishwasher, water under your feet by the creek... it opened up a more microscopic kind of beauty.

–FVASub16 int 2

This motivated use and expanded perception of the content was also connected to *affective value*. Students felt excited, were engrossed, and took pride in their work:

I feel like I'm out of my element, which is fun and exciting.

–FVESub01 int 1

I just had a blast. I was really proud of what I did.... I'm excited to see [the final exhibit]. My family is going to come.

–FVASub07 int 2

That's the way it went every time [with my group]. The longer we did it, the cooler the images got and then three hours go by and we're like okay, just stop!

–FVASub06 int 2

One of my projects, I noticed I can do this and it will look much more interesting. I spent three times as long. I didn't even know it.

–FVESub03 int 2

I started to push myself toward no editing or post processing of the images... be a purist and take a photograph that is all settings, and don't do anything after that.

–FVESub09 int 2

Notice in the last two comments that the affective value is in the context of an aesthetic experience. Granted, it results in opposite reactions – Subject 3 found himself more engrossed in the post-processing of the image, while for Subject 9, a deepening of aesthetic engagement meant pushing himself to “all settings”, meaning using his camera to get the exact image he desired, in the moment. This indicates again the link between affect and aesthetics.

Some trends in the interview data surfaced unexpected similarities between the two groups and the benefits of collaboration between the groups. This included acknowledgement of the other group's expertise:

[The engineer's explanation] went whoosh, right over my head. I didn't understand the physics and mathematics, but I understood why that reaction occurred in simple terms.

–FVASub02 int 2

There were a lot of things that [the film maker] pointed out that I wouldn't have thought of when taking photographs, certain angles, certain lighting... all this art technical stuff. I had no idea what he was talking about.

–FVESub03 int 2

The engineers were looking deeper into what we were seeing. I wouldn't have done that before. I think it's cool. I do value it.

–FVASub07 int 2

[The artists' images] topped all of us. They were hard core.... And they had so much really good feedback, like “you should try that in black and white” or “next time use a higher ISO.”

–FVESub01 int 2

When the engineers presented their [first] projects, I was just like wow! I never could have done that, without the knowledge and background that they have.

–FVASub06 int 1

This mutual respect contributed to collaborative work among the teams:

We played off of each other perfectly because they were just interested in making the experiment and I was interested in capturing it.

–FVASub16 int 2

[The engineering student] had an idea and then I helped him get it to how he wanted it to look and then it kind of all worked together. I was just helping him learn the camera.

–FVASub05 int 2

Another point in common: both groups expressed a dislike for the papers (written after the images are presented in class) with a begrudging appreciation for what they learned through the writing process:

There's times I'm really interested in something and I don't know why... But to have it thought out and put down on paper really helps me think about it creatively.

–FVASub16 int 2

[The paper] backs the image up, gives a secondary way to understand what is going on, maybe more in depth. Maybe the video brings you and makes you want to understand it, and then you can read that and figure out what you just watched.

–FVASub05 int 2

The only thing that I didn't like was writing the papers. The engineering part, I wrote like I normally write any experimental paper. But for the artistic side I felt like I was telling more of a story. I didn't expect that. I liked the storytelling part of it.

–FVESub03 int 2

I think I have a better understanding about what the Reynolds number actually means from [writing the papers]. After my fluids class, you think it's just this number. It can actually tell you a lot.

–FVESub09 int 2

However, the requirement of the paper discouraged at least one art student from taking more risks with the work:

If I could omit the scientific part [of the paper], I would have liked that. It made me reluctant to try things more complex, because I'm like, oh shit after I do this, I'm going to have to explain this scientifically.

–FVASub16 int 2

This engineering / art student comparison reinforced findings from other analysis of the data, including the motivating value of aesthetic experience and the importance of open-ended assignments.

Overall, we found that comparing the two groups revealed:

- 1) The two groups tend to get something different out of the course. The engineers tend to value the hands-on component of creating the fluid flows more, and the artists tend to value the opportunity to document or “capture” those flows.
- 2) By working together, both on teams and by receiving feedback in class, students grow to value the expertise of the other group.
- 3) The written component of the assignments was necessary for students to reflect on what they did, from both scientific and artistic points of view.

Similar Teaching Methods, New Content Domain

A potential critique of our work with Flow Vis and Fluid Mechanics is that it is too specific to one content domain. In other words, how much of what we discover in that investigation is so specific to fluids, that it is not useful in other courses? In some sense, our *process reliability* needed to be tried in another domain (Walther et al., 2013). A new course, focused on design, gave us the opportunity to fully explore our second line of inquiry about teaching methods: *What teaching methods and learning activities contribute to a transformative experience for students learning engineering?*

Flow Vis has several unusual teaching methods, when compared to other engineering courses. We identified the following six features:

- 1) Resource Teams – teammates support each other, with each student still producing individual work
- 2) Aesthetics – equal emphasis with scientific qualities of the images
- 3) Creativity – novel images are valued more
- 4) Choice – the assignments are open-ended, and do not require students document particular phenomena
- 5) Public Presentation and Critique – each image is presented for feedback from the instructor and class
- 6) Heterogeneity of Students – mixing art/film and engineering students

As described in Chapter 4, a new design course using these features was developed, called Aesthetics of Design (Aes Des). While our intention was to use all six features, attempts to recruit sculptors,

painters, and other artists for the course were unsuccessful. However, the remaining five features were fully incorporated into the new course:

- 1) Resource teams – students were grouped with mixtures of expertise, with each student still producing individual work
- 2) Aesthetics – given equal emphasis with the function of their designs
- 3) Creativity – novel design elements were valued
- 4) Choice – the only stipulation was that the object be dynamic in some way, otherwise the project was open-ended
- 5) Public presentation and critique – the course included three design reviews, the final one open to the public

Unlike Flow Vis, this course was taught by three instructors, a new feature that that may have had a significant effect on student learning. We analyzed interview data and survey responses, similar to the process for Flow Vis and Fluid Mechanics.

Aesthetics of Design Survey Findings

The survey for Aes Des used the FluPer survey as its basis, but the new survey instrument did not have enough range. The students hit the “ceiling” in the pre-course survey, giving no measurement of increased interest. For instance, when asked to indicate their strength of agreement with the statement “Studying design is useful to me, professionally,” most students responded with the highest level of agreement – in both the pre- and post-course surveys. Another indication of the ceiling effect is that the average response for both the pre- and post-course survey for “How often do you both notice and think about design outside of classwork?” was “several times a day.” This indicates that student had pre-existing high levels of perception in the area of design.

All of the results from the numerically-scored portion of the survey showed a similar result; students were already intensely interested in design. The non-parametric tests we conducted showed that students did not shift at all in rank for six of the nine questions. While we hope that this indicates a strong

preexisting positive affect for design courses, we acknowledge two other confounding factors. First, the survey may not be adapted correctly for its new context, and second, the compressed course format meant less time for students to shift their attitudes. As with the FluPer survey, what we noticed was how *little* shift in attitude we saw in the Aesthetics of Design course. Table 6.5 depicts the full results. To examine Aes Des further, we turned to the open response questions and the interviews.

Aesthetics of Design Survey	Wilcoxon	
	p	z
Q6.1 (want to study)	1.000	0.000
Q6.2 (useful to society)	1.000	0.000
Q6.3 (useful to me)	1.000	0.000
Q6.4 (can study)	1.000	0.000
Q6.5 (hard course)	0.083	-1.732
Q6.6 (fun course)	0.763	-0.302
Q9 (beautiful)	1.000	0.000
Q10 (fun)	1.000	0.000
Q13 (how often)	0.755	-0.312

Table 6.5: Wilcoxon Signed Ranks Test for Aesthetics of Design, from Summer 2014.

No differences from pre to semester were statistically significant ($p \geq 0.05$ for all questions). A negative z-score indicates a shift toward disagreement for the statement.

Achieving the Learning Objective

We wanted to understand how the teaching methods borrowed from Flow Vis functioned in this new content setting. One way of analyzing the learning taking place in a course is by creating a learning conjecture map (Sandoval, 2014). Figure 6.1 shows the learning conjecture map formed around the primary intended learning objective of Aes Des, which is for students to consider both function and aesthetics in future design tasks³². In a conjecture map, embodiments are structures designed by the instructors, mediating processes are the ways students take up or use those embodiments, and outcomes are what result. If things go as planned; these are the learning objectives of the course. Arrows connect embodiments, mediating processes, and outcomes found to be linked.

³² The original intent of the course was to create transformative experiences for students related to a new content area, design. However, in practice, we needed to phrase the goal more concretely for students.

The dashed lines in Figure 6.1 reflect an unintended outcome of the course. In line with typical course demands, which place a high value on finishing a functional product, some students short-circuited the focus on aesthetics in favor of a more complete final project. Two students commented on this drive to complete the projects as a lack of ambition among their classmates. When asked if some students had “played it safe” ADSub22 remarked, “If I had to put a number on it, I’d say 75 to 25 playing it safe versus really stretching their skills.”

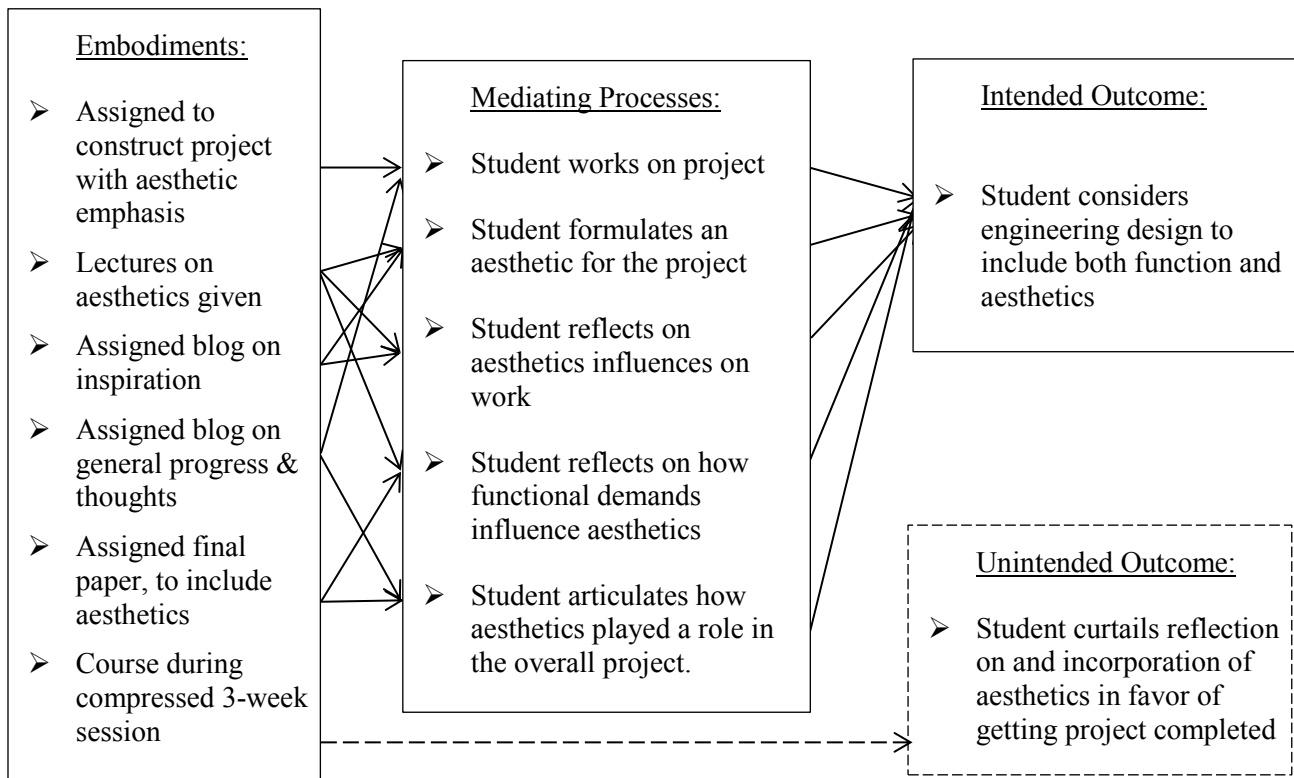


Figure 6.1: Learning Conjecture Map with Intended Learning Outcome

In one post-course interview, a student commented that discussion of aesthetics concepts were cut off by time pressure, because some students felt the “need to go to machine lab rather than asking questions about lecture” and “people were really focused on finishing their projects and less focused on getting the idea of aesthetics and maybe how to integrate them” (ADSub13).

Echoing this view, three survey respondents simply said “more time” when asked the question “Is there anything else you think this class should include?” On a related question, “What would you have done differently if this was a full semester class?” students indicated they would have been more aligned with the goal of the course, if given more time:

I would have focused more on aesthetics.

–ADSub01

More iterations, user testing for usability/aesthetics.

–ADSub06

And they would have taken more time for reflection on their design choices:

Thought more about the motivations behind my design. Also spent time engaging with other students about their designs.

–ADSub13

This material would have gotten more of the attention it deserves, with more contemplation.

–ADSub14

When asked “What did you learn that was new to you?”, thirteen of the twenty respondents (65%) indicated some kind of aesthetic principle, either by listing a specific designer or artist (“Wayne White” ADSub08) or by indicating a general new awareness of the connection between art and engineering (“really help me to see the artistic side of design” ADSub16).

Regarding the blog, 65% of respondents indicated that it was a helpful tool in their work, although several commented that they wished other students had had time to comment on each other’s blogs more, and a couple said they would rather have used a physical design notebook. One interview participant summed up his thoughts on the blog by saying, “we have these lectures on different aesthetics ...the blog helps you to really reflect on what was talked about and let it kind of seep into your work that you're actually doing” (ADSub22).

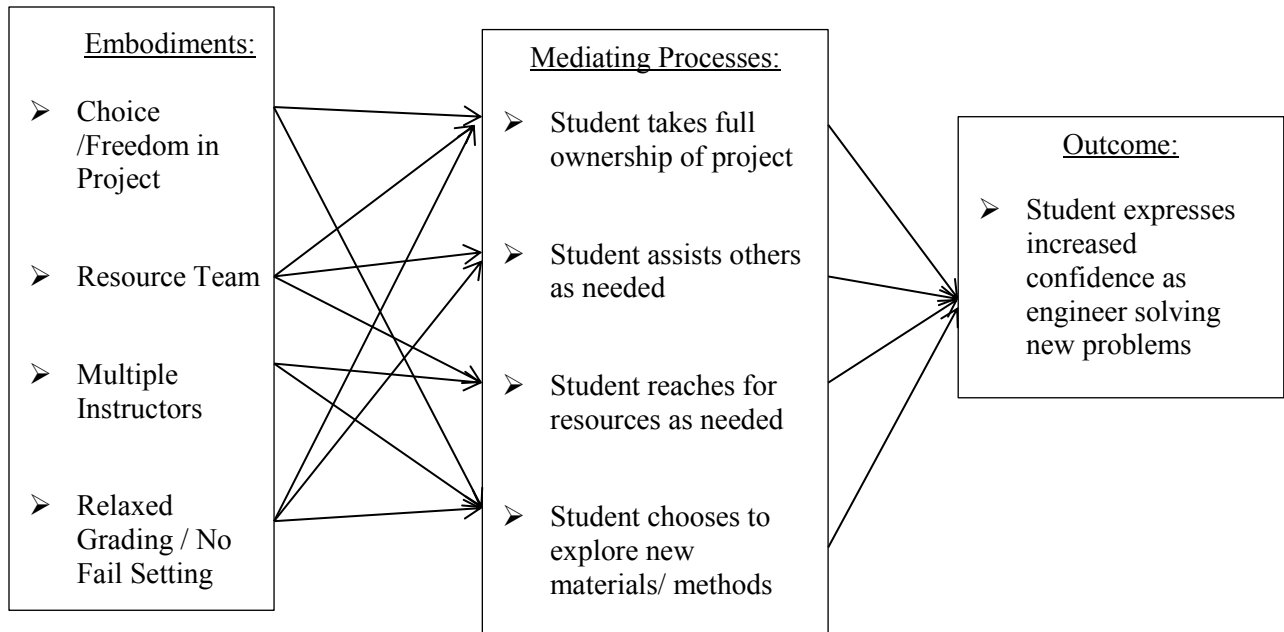


Figure 6.2: Learning Conjecture Map with Unintended Learning Outcome

While the time constraints of this particular format for the course created some counterproductive influences, for the most part, the structure of the course supported students attaining the stated goal of the course, that they will consider aesthetics in future design projects.

Surprising Outcomes in Aesthetics of Design

I think the most valuable experience is how I failed and then how I dealt with it. I'm satisfied.

–ADSub02

When we further examined the Aes Des data, a new set of mediating processes surfaced. We organized these emergent findings in a second conjecture map, Figure 6.2. The embodiments in this second conjecture map are similar to the teaching practices modeled after Flow Vis. These embodiments work together to allow students to take risks and stretch their abilities, by dismantling some of the typical student competitiveness. Although they still judged their projects based on how “ambitious” the projects appeared to be in comparison with others, that tendency was softened by the mediating processes. The structure of the teams, with the diversity of skills, and the sense of collaboration while keeping ownership of their individual projects, contributed both to freedom of expression and sense of cooperation:

[my teammates were helpful because] one of them had experience with manufacturing and the other one had more experience with electronics.

–ADSub02

There was definitely some good discussion for each project of possibilities ...someone suggested using a particular manufacturing method and that was really helpful.

–ADSub22

[When I had problems I told] my group about it, and they started giving me ideas and helped me scale back and re-envision what I wanted, which was nice.... [When another teammate ran into major difficulties] he ended up going another direction...that we kind of helped him with.” (later in the same interview) “Since this class wasn’t curved or anything...**no one wants to see anyone else fail so everyone was helpful** in trying to give good advice.

–ADSub21, emphasis added.

The dynamic was a little different [than other group projects] but I really enjoyed it. I think people felt **more open to give opinions** because whether you use them or not, it wasn’t really affecting them.... There can be tension in groups because you’re working together and people have opposing ideas and then you have to decide which one to implement and make everyone happy, whereas here ... you could decide and **people weren’t offended if you didn’t like their ideas.**

–ADSub13, emphasis added.

Not all teams functioned smoothly, as four survey respondents specifically indicated, one of which also commented, “honestly the most useful thing I learned might have been to reflect on my behavior when working in a team setting” (ADSub18). This generally-supportive environment encouraged students to learn new techniques or work with new materials. Survey respondents cited new skills such as “learned about pumps” (ADSub20), “gear modeling” (ADSub04), or “a lot of new machining and construction techniques” (ADSub19). Several students sought out the instructor with an electrical engineering background to learn to program an Arduino. Overall, eleven respondents (55%) commented on specific new manufacturing methods they tried, new tools they learned to use, or new materials they worked with.

As illustrated in Figure 6.2, these features of the course (choice of project, resource teams, multiple instructors, relaxed grading standard) combined to influence students to take ownership of their projects, to feel free to assist others, to reach out for resources as needed, and to explore new construction methods. For example, in one interview, the student indicated that the combination of choosing the project and

feeling like there would be no punishment for failure encouraged him, even when his project did not function as planned:

[The professor] wants us to struggle, she wants us to go through, and in the same time not punish us for failing. It's not about how well you do compared to others, it's about how you really put in the hard effort and develop yourself, which is unlike any of the other classes. Other classes are based on competition. This one is totally based on self-improvement...because that's what happened in the end when I sort of felt like I failed, you know. But she was like, look what you learned, which made me feel so great because I did learn a lot.

–ADSub02

This remark seems more significant in light of this particular subject's other comments about competition, and that he judged his project to be “in the top five most ambitious projects.”

Several survey respondents commented on the need for self-reliance as well as the importance of outside assistance. This seeming dichotomy mirrors the behavior in professional environments for engineers, where there is an expectation both to complete work independently and voice the need for assistance, locating resources and solutions when setbacks occur.

Finally, these mediating processes combine for a remarkable outcome: students felt more confident in their ability to be engineers. From the survey:

[The best part of the class was] making something that is completely your own. All the mistakes are your fault

–ADSub06

I managed to find way to incorporate aesthetics into engineering in ways that I had not before

–ADSub13

I feel like I grew exponentially... I feel like the creation of [my project] really stretched my understanding about art, mechanical systems, manufacturing, tolerances and working with people.

–ADSub12

From an interview:

My confidence to succeed as an engineer has increased and in this class it was because I was able to tackle a whole new method that I didn't know anything about and then do it successfully.

–ADSub22

The last observation is all the more striking because this student was a graduating senior. The subject had already walked at graduation and was taking one final summer course to officially complete his degree. Many of the other students who responded similarly were upperclassman and graduate students, a group we expected to already feel a higher level of confidence. While other learning outcomes certainly occurred, this recurring theme of intense growth or confidence in abilities appeared to develop from a particular set of balances: self-reliance with leveraging resources, offering and accepting honest critique, and risk-taking in a supportive environment.

Understanding our Findings through the Transformative Experience

Although we have referred to the transformative experience (TE) throughout our findings, re-centering on the TE and our research questions is a means of focusing on what these findings may genuinely reveal. Greater creativity through flexible assignments has been a recurring theme throughout the findings.

Our primary research question asks: *How can educators promote student progress toward a transformative experience, and reliably measure progress toward that goal?*

Germane for the latter half of that question, we have seen that accurately measuring the qualities of TE, particularly affective value, is difficult. Survey instruments and interviews rely on students' sincere participation. Social desirability bias and acquiescence bias, which is when subjects tend to agree with the questions they are asked regardless of their real attitudes, may both be influencing these findings, in addition to the survey fatigue resulting in somewhat glib answers. Also, even though the survey had passed preliminary validation, it did not provide the range to capture student changes in attitude for the

courses in question. Future work could develop a new survey, perhaps following the Rasch model, which explicitly tests for overfit (M. Wilson, 2005).

Despite these challenges with the closed response survey results, upon examining the open response items, four types of interest emerged. These categories, which students gave as the reasons they were interested in fluids, we summarized as *complexity*, *application*, *ubiquity*, and *aesthetics*. The four categories may provide us with additional means to engage students. When reviewing the format of assignments, we could ask ourselves, are we tapping into more than one category of interest? Can we engage more students by being mindful in this way about our assignment design?

We did not see substantial shifts among the four categories of interest for students from beginning to end of the courses, nor did we observe substantial shifts in affective responses. We did see overall higher levels of positive affect among the Flow Vis students, an understandable result among students taking an elective, versus the Fluid Mechanics students taking a required course. The same positive affect resulting from the choice of elective appears again in open-ended assignments, where students are also afforded more choice. We explored the effects of the open-ended assignments in Flow Vis, in contrast to the highly structured work in Fluid Mechanics, and found benefits from both sorts of work. We discovered students have both a need for highly structured assignments, where both methods and right answers are relatively straightforward, and open-ended assignments that allowed them to be more playful with their ideas and knowledge. However, there is a lack of balance. Open-ended assignments appear to be far rarer, yet they can fuel both motivation and creativity. The relaxed grading system for those open-ended assignments generated one discernable area of demotivation for the Flow Vis students: the perception that they were receiving the same reward yet working harder than the students taking the work less seriously.

As we sought to address the first line of inquiry of our research question, (In the context of a specific engineering domain, what is the relationship between student affect and a concurrent expansion of perception?), we examined the interview data for expansion of perception in the area of fluid physics. We

detected an expansion of perception, but we were surprised to find it associated more broadly with how students thought of themselves as engineers, rather than within the more narrow confines of a specific course or a specific content domain. Most of our interviewees' stories of expanded perception were tinged with awe, fascination, and curiosity, namely, *affective value*. These anecdotes emerged voluntarily in the course of our semi-structured interviews. We found that expansions of perception that lacked these affective traits stemmed from interests focused on the application of knowledge, similar to Twain gaining the ability to pilot his riverboat. Our conclusion is that developing multiple types of interest would better fuel student motivation, and perhaps lead to TE. Aesthetics, in particular, seems potentially ripe for further development, as the detailed look at engineering and art students highlighted, echoing Feynman's delight in how science added to the beauty of a flower.

For our second line of inquiry: (What teaching methods and learning activities contribute to a transformative experience for students learning engineering?), we examined how the five unusual features of Flow Vis functioned when moved to the context of a design course. That course, Aesthetics of Design, included *resource teams, an emphasis on aesthetics, a focus on creativity, an open-ended project, and public presentation and critique*. While our survey had the same shortcomings in this area as it had in Flow Vis, we were able to ascertain from open responses and interview data several interesting outcomes. We displayed these outcomes on conjecture maps, a graphic tool intended to make it easier to map professor's design of the course (*embodiments*) to students' engagement with the course (*mediating processes*) to the learning outcomes. Students shared few moments of *expanded perception*, but they did demonstrate what might be termed scaffolded *motivated use* of content. Many took risks, in the form of learning new skills, and reported a gain in confidence in themselves as engineers as a result.

Finally, as we explored the possibilities when Flow Vis-like teaching methods were attempted in a new content domain, we found that giving students open-ended assignments allowed them to choose the amount and types of challenges they wanted to pursue. We do not have full understanding of students' past experiences, as Dewey might prefer, in order to create their ideal learning environments (Dewey,

1938), but by giving the students the opportunity to choose their own projects, as in Aesthetics of Design, they chose to challenge themselves, often selecting materials or methods new to them. This resulted in them each working in their own Zones of Proximal Development (Vygotsky, 1978). The resource teams, as well as expertise from instructors, were sources of “more knowledgeable others” who could assist as needed on their individualized projects. The experiences that result, while not fully in line with the definition of transformative experience, come close to creating Csikszentmihalyi’s *flow* (Csikszentmihalyi, 1990).

Much of the value of these courses, Flow Visualization and Aesthetics of Design, seems to come from the broadly open-ended assignments within fully supportive environments where that support comes from both instructors and teammates. By engaging students with multiple sources of interest (complexity, applicability, ubiquity, aesthetics) and allowing them to choose their own challenges, students not only achieve their stated learning objectives, but stretch beyond to contribute to the overall goal of their education: increasing their confidence in becoming engineers.

Chapter 7 – Methods and Results in Studying Perceptual Expertise

This portion of our work is motivated by a desire to develop a link between measurable perceptual expertise and the self-reported expansions of perception examined in earlier chapters. As expressed in the third line of inquiry of the primary research question on Perception: *What is the link between perceptual expertise and the transformative experience? How can we measure perceptual expertise in a particular engineering domain, such as fluid dynamics?*

To create that connection, we modeled our investigation on those of other types of perceptual expertise, such as face recognition and experts' encoding and memory of cars and birds. This chapter has two sections. The first details our methodology. We model our methods after a paradigm used by well-received and replicated studies, summarized below. This is followed by the specific methods used in our experiment, and then the statistical procedure used to analyze the resulting data. The second section details our findings and discusses our results.

The work described here aims to define and establish a measure of visual expertise in fluid physics, in the specific dimension of laminar versus turbulent flow. While real-world expertise takes months or years to be developed, we can still learn from these training studies, because they “allow for the manipulation of different factors that may contribute to the acquisition of expertise, providing better control over variables influencing this process” and “also allow for better manipulations of the factors that lead to more or less generalization” (Scott et al., 2009). Generalization, often discussed as learning transfer, is at the heart of our objective for this study.

Although it may be a long process to connect these experiments to the classroom, the ultimate goal is to create measures that help us determine if a course is successful in helping students gain perceptual expertise, both relevant and generalizable, in that field.

Methodology

Prior Work

Tanaka, Curran and Sheinberg (2005) was one of the first studies to use the experimental paradigm we emulate. Earlier research established that experts are able to go directly to subordinate level identifications, bypassing the basic levels novices go through (Tanaka & Taylor, 1991). For example, a basic level of a stimulus might be *bird*, with the subordinate level being *crow* or *robin*, and a basic level *dog* would have subordinate levels such as *poodle* or *beagle*. In that study, researchers asked “to what extent does subordinate-level learning contribute to the transfer of perceptual expertise to novel exemplars and novel categories?” In other words, if expert subjects can identify a particular image of an object, are they also better at identifying new images of that object and new categories of related objects? For this experiment, images of birds were used: 10 owl species and 10 wading bird species. Participants were trained over six days, with final testing on the seventh day. Testing was conducted using a *sequential matching task*, where the subject is shown two images, one after the other, and must respond whether the birds shown are the same or different. One of the training tasks was a *naming task*, where the subject is shown a single image and must indicate (or name) the correct category for the image.

Tanaka et al. (2005) discovered that, for example, subjects trained at the subordinate level (on individual owl species) could not only identify new images of the owl species they were familiar with, but they were also able to learn new owl species more quickly. That is, their training did indeed *generalize* to novel exemplars and to novel categories. However, when learning at the basic level (wading birds), subjects did not demonstrate any generalization, and there was no improvement on basic level identification response times. The subjects had to *do the task* of noticing differences and categorizing the species in order to gain the perceptual expertise. Mere exposure to all the images was not enough.

The results from the Tanaka et al. 2005 study were replicated by Scott, Tanaka, Sheinberg, & Curran (2006). This study, also using bird images, included the important addition of looking at subjects’ brain

responses to stimuli, measured in the form of event-related potentials (ERPs). The results from the 2006 study were then replicated and extended by Scott and her colleagues (Scott, Tanaka, Sheinberg, & Curran, 2008). This third study, which used images of cars, included a final assessment after a one week delay. They found that subordinate level training increased performance, even after that delay, whereas basic level training did not.

Methods

Following Tanaka, Curran and Sheinberg (2005), we created a perceptual expertise experiment. After initial testing (Goodman, Hertzberg, Curran, & Finkelstein, 2015), we chose to use static images of fluid flows that could be sorted as laminar or turbulent in a single session experiment, testing two kinds of subjects: those with no prior technical knowledge of fluids, and those who had passed a college-level fluids course.

Participants

Subjects were ages 18-30, with normal or corrected-to-normal vision. They gave informed consent to participate in the study, as per the protocol approved by the Institutional Review Board³³. Subjects were recruited via fliers, email, and classroom announcements. They trained individually and were paid \$10 per hour for their participation. The experiment recruited self-reported novices in fluid dynamics (n= 57) and relative “fluids experts” (n= 39) by recruiting students who had completed fluids courses.

Materials

This experiment was programmed in MATLAB (version R2013b, The MathWorks, Inc., Natick, MA) using a locally-developed experimental framework³⁴ and presented with Psychtoolbox, an open source set of functions for vision and neuroscience research (Brainard, 1997). This allowed the experiment to be presented on a computer, limiting what keys or other controls the subject could use. Subjects viewed the

³³ IRB protocol #14-088

³⁴ See <https://github.com/warmlogic/expertTrain>

experiment on 17-inch flat-panel displays with a resolution of 1024×768 (60 Hz frame rate) placed one meter in front of the participants, and used a standard QWERTY keyboard.

Image Selection and Processing

For this experiment, the categories of images were turbulent and laminar fluid flows collected from online sources. To verify that images were correctly classified as either turbulent or laminar, we asked two experts (mechanical engineering professors who regularly teach fluids) to classify them independently. If an image was in doubt or labeled “transitional” by either expert, it was not included in the study. One specific type of image used was of Von Kármán vortex streets, which are seen when a fluid flows past an obstacle, and the wake becomes a series of vortices. This type of fluid flow can be either turbulent or laminar. Twenty images of each category were included as stimuli for the experiment for a total of 40 vortex street images. Another group of images (called “general”) contained a wide variety of flows, none of which were vortex streets. These were also categorized as either laminar or turbulent, and likewise, 20 images from each category were included. Thus, our four groups of images were:

- 1) Laminar instances of Von Kármán vortex streets
- 2) Turbulent instances of Von Kármán vortex streets
- 3) Laminar instances of general flows (all non-vortex streets)
- 4) Turbulent instances of general flows (all non-vortex streets)

See Figure 7.1 for examples from each group of image.

Several steps were taken to remove extraneous visual information from the images. All images were processed to be gray-scale, no larger than 450 x 450 pixels, and no less than 230 x 230 pixels. All vortex street images were oriented with the flow going from left to right. All portions of the display not covered in images or text during the experiment were presented as gray pixels.



Figure 7.1: Processed image examples.

1) Top left – laminar vortex street (Griffin & Votaw, 1972) 2) Top right – turbulent vortex street (Sakamoto & Arie, 1983) 3) Bottom left – laminar general flow (C. Miller, 2014) 4) Bottom right – turbulent general flow (Lim, 2014)

Experiment Design

Subjects received instructions that covered what to expect from the format of the experiment, but no information regarding the nature of the images they would see or what the categories would be. The experiment was conducted in a single session. Within the text of the experiment, the categories were called 1 and 2 to avoid any misinterpretation due to subjects' prior familiarity with the words "turbulent" and "laminar." Two different types of tasks were used:

- Matching task: subject shown two images, sequentially, and must indicate whether the two images are in the same or different categories. The sequential matching task was used for testing, and subjects received no feedback.
- Naming task: subject shown a single image, and must indicate if the image fits category one or two. For our experiment, this was used as the training phase, and subjects received feedback for their actions. When correct, they saw a green-colored "Correct!" and heard a high-pitched beep, and when incorrect, they saw a red-colored "Incorrect" and heard a low-pitched beep.

At the start of the session, subjects completed brief practice tasks in matching and naming, using images unrelated to the experiment, to learn the controls for the experiment.

Subjects were split into two groups. Odd-numbered subjects were given the pretest, training, and posttest on Von Kármán vortex streets, and a final test on the general group of images. Even-numbered subjects were given general images for the pretest, training, and posttest, and a final test on Von Kármán vortex streets. These final tests were called alt-tests, as subjects saw images from the other group's set. See Table 7.1 for experiment phases with numbers of trials for each. During the experiment, half of the images from each category were selected randomly for the training task, while all images were used for the testing tasks. This was done to determine if training generalized to the untrained images, and to prevent subjects from showing improvement through memorizing individual images.

Task (phase)	Pretest (Match 1)	Training (Name)	Posttest (Match 2)	Alt-Test (Match 3)
V.Street-trained subjects	Vortex Streets (40 trials)	Vortex Street (20)	Vortex Streets (40)	General Flows (40)
General-trained subjects	General Flows (40 trials)	General Flows (20)	General Flows (40)	Vortex Streets (40)

Table 7.1: Phases of experiment with types of images and number of trials for each.

Both fluids novices and fluids experts were split into these two training groups, such that we had four groups to examine:

- 1) Novices trained on vortex streets (n=28)
- 2) Novices trained on general flows (n=28)
- 3) Experts trained on vortex streets (n=19)
- 4) Experts trained on general flows (n=18).

At the end of the experiment, subjects were asked to write responses for two concept questions:

- 1) Thinking about your experience in the experiment, how would you describe the two categories of images?

2) How did you decide which images to place in which category?

Lastly, the subjects completed a brief demographic survey.

Statistical Procedure

To determine whether subjects were able to learn the categories in the brief training task, and then to see if they were able to transfer that learning to the alternate set of images, we recorded their accuracy for each testing phase. Results for each testing phase (pre, post, alt) were tallied including hits and false alarms (false positives). For each subject, a sensitivity index (d') was calculated, a measure commonly used in signal detection theory to separate the signal from the noise. In this case, it allowed us to measure subjects' ability to respond to both types of trials (where "same" was the correct answer and those where "different" was correct), while taking into account response bias for subjects who tended to press the same key regardless of the stimuli. A 3x2 Multivariate Analysis of Variance (MANOVA) was calculated, with three levels of test (pre, post, alt) and two levels of subjects (novice, expert).

The concept questions were logged, and the expert subject responses were sorted by those who clearly wrote that they were using categories of laminar and turbulent in the experiment, and those who did not correctly name the categories. The subjects' responses had to note at least one of the key words "laminar" or "turbulent" in their descriptions in order to remain in the pool. Using this verified set of experts, we recalculated the MANOVA. Because we were interested in the expansion of perception, as related to the field of fluids, we focused on the pool that had made this connection.

Findings and Discussion for Study of Perception

Data Preparation

Data from three subjects (one novice, two experts) became corrupted and were removed from the analysis. Thus, data from a total of 56 novice subjects and 37 expert subjects were analyzed. We looked for outliers whose performance on any one test phase was more than three standard deviations away from

the mean score, and removed one expert subject from the data as a consequence. That subject's data revealed a very high false alarm (false positive) rate. In fact, it appears the subject responded with the same key for 39 of the 40 trials in the alternate testing phase. The sensitivity index (d') was calculated for the remaining subjects (Novices, $n=56$; Experts, $n=36$). After examining the concept question responses, we found that nine of the expert subjects had not identified their task as sorting laminar and turbulent flow. We labeled the remaining pool ($n=27$) as "verified" experts and completed a second round of analysis.

Findings

We calculated the sensitivity index (d') for accuracy of responses by testing phase for novices versus experts, and then novices versus the smaller group of verified experts, yielding the results reported in Table 7.2. While phase effect and the interactions of phase by group and phase by group by training were all statistically significant when using the verified experts, only the phase effect and phase by group by training interaction were significant when using the entire group of experts.

	Phase	Phase x Group	Phase x Group x Training
Novices (n=56) x Experts (n=36)	F(2,87) = 25.548, p<0.001*	F(2,87) = 2.908, p=0.060	F(2,87) = 5.074, p=0.008*
Novices (n=56) x Verified Experts (n=27)	F(2,78) = 25.853, p<0.001*	F(2,78) = 4.301, p=0.017*	F(2,78) = 5.117, p=0.008*

Table 7.2: The F test results from MANOVA testing.

* indicates statistical significance ($p < 0.05$).

Examining the results, we focused on the comparison of novices and verified experts, who were shown to have recognized their task as sorting laminar and turbulent flows. (From here forward, "experts" refers to this narrowed group.) We found significant differences between testing phases, confirming that the training was effective (posttest results were significantly better than pretest). The analysis revealed a significant interaction between testing phases and group (i.e. novice or expert), as well as by phases, group and training type (vortex-trained vs. generally-trained). The phase by training interaction was not

significant because, as shown in Figure 7.2, the novices and experts had opposite trends for the posttest when compared with the test of alternate images, as captured by the significant three-way interaction. Note that $d' = 0$ indicates responses were roughly the same as chance (50% accuracy), $d' = 1$ is approximately 70% accuracy, while $d' = 2$ is roughly 84 % correct.

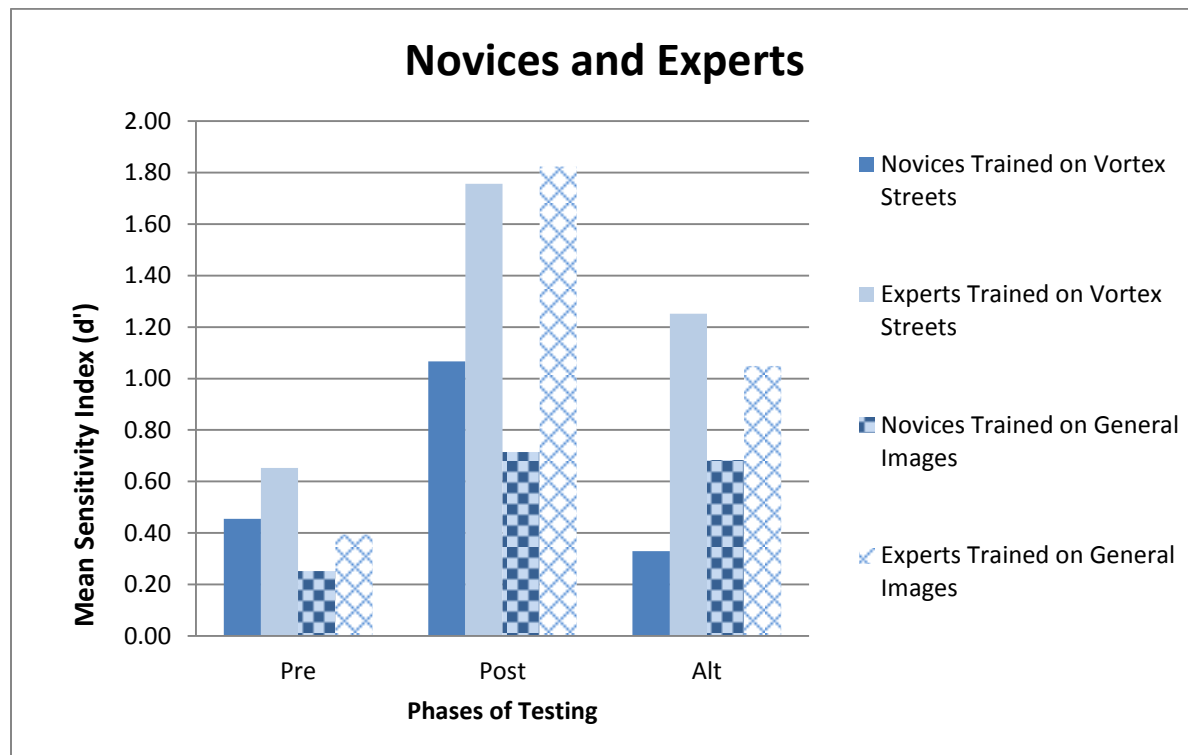


Figure 7.2. Results for Novices (dark bars) and verified Experts (light bars) as calculated by d' , for each phase of testing and divided by training. Solid bars indicate subjects were trained on vortex street images, and performed the alt test with general images. Patterned bars indicate subjects were trained on general images, and performed the alt test with images of vortex streets.

Note that the novices exhibit a similar result as other visual expertise studies – that training on specific instances (vortex streets) results in greater learning for that subordinate level of stimuli, yet that training does not transfer well to broader categories. In contrast, training with a broader group of images (general images) results in lower learning gains in the posttest, but those gains tend to be maintained when presented with the new set of images (Scott et al., 2009). This can be observed in our data by comparing the novices trained on vortex streets (dark solid) to those trained on general images (dark patterned).

This is not true for the experts. Unlike the novices, the differences by training within the expert group were not significant. Experts did not exhibit the same pattern of transfer from specific to general categories of images, or vice versa, as novices. The general or specific nature of the training stimuli seems to matter for the novices, but not for the experts. This suggests a different underlying process for the experts.

Discussion

In one sense, these expert subjects are displaying a type of transfer. They are, without explicit prompting regarding the category labels, reporting that their task was sorting laminar and turbulent flows. Some may argue that this result is not noteworthy when taken in full context. After all, subjects were alerted to the involvement of fluids content because recruiting efforts mentioned the need for subjects with and without that experience. Moreover, subjects were asked to which group they belonged as they signed in for the experiment. Future studies may want to alter recruitment methods in order to avoid mentioning the content area of the stimuli prior to testing. One approach might be to recruit solely from engineering courses that have Fluid Mechanics as a prerequisite, which would eliminate the need to explicitly mention fluids. A questionnaire after testing could confirm this precondition, so that the question would not prime the subjects for a fluids-oriented task beforehand.

In another sense, however, the expert subjects' transfer of knowledge is in fact noteworthy. This task is probably unlike those they have performed in any other context. The work required for Fluid Mechanics courses tends to be analytical, focused on solving equations. The use of images in the course is limited. Some students may have used drawings to aid their comprehension, and some professors expose students to images of fluid flows and discuss these images in class. In fact, many professors who teach the students we interviewed show a "Flow Vis of the Day" during their Fluid Mechanics courses. However, tasks involving analysis of images of fluid flows are rare. From Tanaka, Curran and Sheinberg (2005), we have evidence in a laboratory setting that exposure to images was not sufficient for subjects to learn to distinguish between stimuli categories at the subordinate level. They found participants had to perform

the sorting tasks in order to gain the perceptual expertise. In our case, expert subjects were applying what they knew outside of the testing context to a new task. Accordingly, our result is not directly analogous to the original Tanaka study, and does not challenge their findings. This study is also not comparable to studies that engaged bird and car experts. Bird watchers, in particular, commonly use their expertise in visual tasks. In contrast, our fluids experts did not typically employ their fluids expertise to do visual tasks prior to the study.

What our study does suggest is a crossover between conceptual and visual perception skillsets. Our findings, then, are also related to the studies conducted by Michelene Chi and her colleagues, where physics experts were shown to sort problems differently than physics novices (Chi et al., 1981, 1982). Similarly, we find that fluids experts can apply their expertise to the image sorting task, which is a novel use of their conceptual understanding of fluids. The nine expert subjects who could not identify the categories by the end of the experiment may very well be able to compute Reynolds numbers, the dimensionless quantity often used to determine levels of turbulence, but simply were not able to transfer that understanding to a visual representation. Or, it may suggest that they gained the procedural, analytical ability to pass the course, but not the underlying conceptual understanding. We see the ability to map conceptual understanding onto visual information as a necessary step toward the expansion of perception that is part of the transformative experience.

This result may be similar to findings in the Physics Education Research (PER) community. They have documented that students who can correctly use Ohm's law and Kirchhoff's rules to solve complicated quantitative circuit problems often have difficulty with a simpler qualitative task ranking light bulbs in a circuit diagram by brightness (McDermott, 1993). In the PER study, only 15% of the students showed that they can transfer an analytical skill to a visual task. Perhaps what is missing is an underlying conceptual understanding. If handling ideas visually promotes connections between analytical skills (solving equations) and conceptual understanding, then that would be another reason to implement visual tasks in STEM courses.

Several expert subjects in the general-trained group commented that they second-guessed themselves when presented with the vortex streets in the final test phase (alt phase). Recognition that students may doubt what they have learned when confronted with new data or situations is worth further investigation, and may be related to other ways of framing the transfer problem, such as “activating resources” (Hammer, Elby, Scherr, & Redish, 2005). What features of the training phase activated their knowledge of laminar and turbulent flows, such that they knew to apply it to this new task?

The main contribution of this study is that it begins to create a linkage between conceptual learning and visual expertise, with the potential to create an alternate assessment of conceptual understanding in contrast to analytical problem-solving. In education research, mention of a need to engage more than just our analytical sides can evoke discussions of individual students’ “learning styles” (Felder, Mohr, Dietz, & Baker-Ward, 1994). Yet, we would rather that our work promote an emphasis of developing a well-rounded skillset for all students.

This study establishes a viable method of measuring visual perception in a specific dimension of an engineering discipline. Future work should include other concepts from fluids, including jets, shear layers, and Rayleigh-Taylor instabilities, in order to create a more nuanced measure of visual expertise in fluids. We would also like to switch to a web-based platform so that other institutions could more easily join the study. Other future work should continue to explore the connections between visual expertise and conceptual aptitude in particular disciplines, particularly in areas other than fluids. Such work will help further characterize the connection between perceptual expertise and expanded perception as defined in the transformative experience.

Chapter 8 – Conclusions

In this chapter, we summarize our investigation and findings, and highlight the links between our interpretive and experimental results. We then discuss the limitations of this analysis, and propose future work.

Surprises from Interpretive Work

The starting point of this research was a puzzle: what prompted some Flow Vis students to report that they “see fluids all the time” after taking the course? That search led us to the *transformative experience* (TE) as a useful theoretical lens. We confirmed that the *expanded perception* in Flow Vis held *affective value* for the students, but we did not hold out much hope for finding extensive evidence for the third quality of TE, *motivated use*. This part of the construct is described as happening wholly outside of the classroom and is consequently more difficult to locate and measure.

We discovered that certain assignments mimicked motivated use in a form we call *scaffolded* motivated use. The open-ended assignments in Flow Vis and the newly-created Aesthetics of Design comprised the appropriate amount of support for upper-division students ready to synthesize their skills. In these assignments, students form their own ideas, plan out their work, deal with the mistakes or “messes” that result, and given enough time, iterate in their work. As with all engineering projects, students must also write about what they did. The benefits from these types of assignments became clear as we studied the outcomes from Aesthetics of Design. Students reported taking risks by choosing materials or methods that were foreign to them prior to taking the course. They reported reaching out to both instructors and teammates for assistance to accomplish their goals. This activity implies that they were learning in an optimal way, working in their Zones of Proximal Development (ZPD) (Vygotsky, 1978). We see an association here between what these few technical electives accomplish and larger initiatives at other universities, for example, the iFoundry at the University of Illinois. At the iFoundry, engineering students are similarly encouraged to direct their own projects. As one iFoundry student

reflected, “it felt weird at first that we were left to do so much on our own and make our own decisions with our projects. [But in the end] it really gave us a clearer view of what it is like to be an engineer in the real world” (Goldberg & Somerville, 2014, p. 64) This connection, between self-reliance in a project and a stronger sense of engineering identity, relates to our other unexpected finding.

The second surprise, as we applied the TE to engineering education, was the manner in which expanded perception appeared. The greatest association was not between expanded perception and a specific area of content, such as fluids. Instead, students most often reported expansion of perception when they were asked about what it meant to *be* an engineer. While it has been found that self-rated math ability is the variable most closely associated with a sense of belonging in engineering (D. Knight, 2013), discussion of engineering identity in our data was most often associated with a sense of curiosity about how things work, and with anecdotes about students seeing the principles they have learned playing out in the real world. Their examples included different ways of employing technologies or design, the interplay of energy, environmental factors, and fluids. This is what it means to be an engineer for many students: to perceive the world through newly-gained engineering expertise.

Questions Generated through Experiment

Our perceptual expertise experiment with images of laminar and turbulent flow demonstrated 1) that novices learned the abstract concepts used to sort the flow stimuli in ways similar to the concrete categories like species used within prior studies using bird stimuli, and 2) that the subjects with prior fluids knowledge did not undergo the same learning process as the novices. The fluids experts’ results suggested that these subjects were able to access their conceptual knowledge about fluids to perform this new, visual task: sorting the images by whether they were of laminar or turbulent flows. This finding, while seemingly simple, opens the door to new ways of understanding conceptual learning. It causes us to question whether this interaction is two-way. That is, for the novices who learn this visual perception task, would learning the concepts of fluid physics around laminar and turbulent be easier as a result? Also, could we use such a task as a type of assessment in a fluids course, using visual expertise in fluids

images as one benchmark of learning? Perhaps this could be a way to differentiate students who both understand the concepts and can work through the mathematical procedures from those who can complete the math but do not grasp the underlying concepts.

Connections from Experiment to Classroom Practice

This result is not a call for merely inserting more images into fluids courses. We know from prior studies that exposure to images is not enough for subjects to gain the perceptual expertise needed to sort those images at the subordinate level (Tanaka et al., 2005). Similarly, mere exposure to flow images without instruction would likewise be ineffective. As we have seen, beautiful images are often enough to attract students to Flow Vis, but ideally these images would also draw the students' curiosity about what is happening in the images. Even with current limited use as is the case in Fluid Mechanics, such images help cement understanding. As one Fluid Mechanics student stated, "I think I kind of would have got it without the visualization, but I think the visualization really locked in the concepts and the knowledge" (FMSub11 int 2). Thoughtful use of images within lessons can certainly reinforce or connect students who otherwise might not understand the concepts. Perhaps images could be inserted as concept ("clicker") questions during lecture, providing students an opportunity to actively engage in a task using the images.

Beyond being another representation of a problem, flow visualization embodies something more profound. It calls forth our visceral engagement: awe for a thunderhead cloud, whimsy with bubbles, perhaps introspection when gazing into a waterfall. Flow Vis, the course, allows students to address this explicitly emotional side of their work, to turn the scientific into art. Aesthetics of Design also creates a space in which students can directly address the emotional impact of their work by asking students to incorporate a design aesthetic into their projects. This leads us to ask, what is the equivalent perceptual expertise for another engineering field? How would we define another field's *aesthetic*? We are actively pursuing this new line of inquiry in a special session at the Frontiers in Education conference later this year (Hertzberg & Goodman, 2015).

Contributions

This thesis provides two related contributions to engineering education research from a theoretical standpoint. The first is that it demonstrates how the transformative experience can be applied as a useful lens by bringing into focus the interaction among how students see, use, and feel about what they are learning. The second contribution is the framing of the Feynman versus Twain problem: that students can gain the necessary perceptual expertise while losing the ability to enjoy those skills. By naming this largely hidden problem, we can better characterize those times when we drive students away from the very professions for which they are being educated.

This study also contributes recommendations for changing classroom practices. The five features shared by Flow Vis and Aes Des work together to create a supportive, motivating environment for many students:

- **Resource Teams** – students assist their teammates and complete individual assignments, adding support while reducing frustrations about who ‘gets credit’ on collaborative work.
- **Aesthetics** – given equal emphasis as the functional side of the projects, which is both more realistic for marketing actual products and provides a rationale for incorporating personally meaningful features.
- **Creativity** – novel solutions more highly valued. In a time when innovation is expected of every engineer, practice thinking creatively is needed.
- **Public Presentation and Critique** – everyone receives feedback from the instructor and class, modeling the way professionals deliver constructive feedback to each other.

And perhaps most importantly:

- **Choice** – the assignments are largely open-ended as to subject, only the format of the presentations and papers are structured. This feature seemed to stimulate much of the value of the other features. Choice allows students to engage their own sense of aesthetics, to be creative in their work.

Taken together, we believe these features could produce interesting courses in a number of other engineering fields, creating learning environments in which the TE is more likely to occur.

Limitations from Sampling and Sample Size

There are particular limitations to the interpretive work presented here. In addition to *acquiescence bias* and *social desirability bias*, discussed earlier, we also found an interesting sampling problem. Students were invited to participate in the interviews, and were compensated with a small monetary incentive. Sampling may have been biased by which students chose to volunteer. For instance, for Flow Vis, it was easier to find art students to be interviewed (n=5) than engineering students (n=3). Among the Fluid Mechanics interviewees (n=4), we see another odd pattern: none of the students are what could be called “typical” students. One was an applied mathematics major, not a mechanical engineering major; another was double majoring in music performance. One was a non-traditionally aged student returning to school after a long hiatus; another already had earned a bachelor's degree in physics at another institution and was still determining whether he wanted to earn an additional bachelors or a masters in engineering. We cannot tell whether this reflects a decrease in what might be called the “average” engineering student or simply that these students were more drawn to participate in the research, for whatever reason. While we cannot compel students to volunteer for such interviews, we might begin by selecting students at random to be invited to interview, rather than beginning with an open invitation.

There were also limitations with the visual expertise experiment in the form of small sample size. We began by running the experiment in the Psychology Department building, but eventually realized that the specialized engineering population we needed to recruit simply would not walk the fifteen minutes to a different building to participate. Participation increased once the experiment was moved to the Engineering Center. Another limitation was the scope of the experiment itself: we only tested one visual dimension of fluids – laminar versus turbulent flows. A main challenge with creating more dimensions for the experiment was locating and processing suitable images.

Future Work

We are excited by the possibilities for the perceptual expertise study; there are many options for extending this area of our work. More dimensions of fluids should be introduced to the experiment, such

as the contrast between jets and shears, in order to create a useful classroom assessment of perception of fluids. There is also the need to make the experiment web-based, so that its delivery is not limited by the software required to run the current version. We are already looking at potential platforms. Once it can be more widely distributed, there are more options for establishing its relevance. We imagine, for instance, asking fluids experts from around the world to participate with a larger group of images, to create a more definitive range of fluids expertise, not unlike what past studies have measured in bird watchers. This work may also inform studies of the brain. Are the abstract categories of fluid flows activating different brain regions than more concrete stimuli, like cars or faces?

Our work with the courses themselves also has several potential directions. By creating more robust survey instruments, we can give other instructors the means to assess affective interest and expansion of perception related to their courses in a minimally invasive way. We also hope to distribute the surveys for use at other institutions, especially where courses similar to Flow Visualization and Aesthetics of Design are taught.

We are also investigating ways of incorporating Design-Based Research (DBR) into future offerings of the courses (Kelly, 2014; Penuel, Coburn, & Gallagher, 2013). In DBR, instructors and students are participants and co-designers of whatever the research produces, rather than merely being subjects of the research. This research practice places trust in the students in a way not unlike the way open-ended assignments place control in student hands, to be responsible for their own learning. We foresee a productive combination by directly engaging students in the design of a course.

Final Thoughts

The goal of this research was to explore the usefulness of the transformative experience in engineering education. As a theoretical lens for our work, it has been tremendously helpful, by providing a way to focus on the various aspects of student responses most meaningful to our work.

However, we are concerned that some could read this work and use it in counterproductive ways. We imagine assignments aimed too directly at expansion of perception may create results akin to Mark Twain's view of the Mississippi: terribly useful, but devoid of affective value. We are not suggesting we add new batteries of tests, with images flashing before students' eyes like a scene out of *Clockwork Orange*. Likewise, repeated assessments aimed at TE might be like a friend looking over your shoulder as you examine an optical illusion, saying, do you see it now, do you see it now? This would be counterproductive for both expanded perception and affective value. It would certainly make motivated use less likely. This leaves open the question of measuring TE; developing a more reliable survey for different content areas seems the best option (Pugh et al., 2010).

The most promising avenue appears to be the notion of scaffolding motivated use of the content: allowing students to choose their projects to a greater extent, and providing support for their work. Lest we paint too rosy a picture, we recall the concomitant grading frustrations that some students expressed, in both Flow Vis and Aes Des. The same leeway that allowed students to worry less about failing in their bold attempts to try something new caused other students to exhibit lower ambition, while receiving the same grade. To overcome the demotivating effects of the grading system in Flow Vis and Aes Des, we suggest working to create different social norms for the course (Ariely, 2008). We know that students care about 'getting credit' and collaborative work often creates confusion and frustration over whether each student has contributed (Sieber, 2010). *Resource teams*, in which students assist each other while still producing individual work, represent one potential remedy for this problem. Also, some instructors have created prizes for the "best failure" or "biggest risk-taker," that do not factor into grades but reward the behaviors they most want to observe in their students (Pausch, 2008). We suggest these types of prizes should include teamwork behaviors. One option is to allow students to award the prizes to each other, a strategy called "peer-to-peer recognition" also used in business (Vranjes, 2014).

We are also tantalized by the aesthetic potential of other fields of engineering. Fluid physics is not an isolated topic, and certainly not the only engineering field that can be approached aesthetically. There are

other fields we can enjoy visually, or with our other senses. This becomes the new metric for judging the education we make available to students: not whether we cover every equation possible, but whether we give students a window into the creative discipline of engineering.

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Appendix A - Participant Identifiers

To clarify the way we labeled participants, we provide a full identification key. The first part of all identifiers is a two letter indication of the course: FM – Fluid Mechanics, FV – Flow Visualization, and AD – Aesthetics of Design.

If the next characters are numbers, they indicate the year the participant was in the course, 13 indicates the 2013 survey, Fall 2013 for Fluid Mechanics; Spring 2013 for Flow Vis, and 14 indicates the 2014 survey, Spring 2014 for both Fluid Mechanics and Flow Vis.

If instead of a number, the next character is E or A it indicates that these were students interviewed from the Flow Vis course who were either E – engineering majors or A – art majors. All non-engineering majors were categorized as “art”, although they came from fine arts photography, film, and technology, arts, and media programs.

The next portion of the identifier is “Sub” (for subject) followed by a unique two-digit number. That may be followed by “int 1” or “int 2,” which indicates whether the quotation is from a first or second interview. Note that for Aes Des, subject numbers were retained for the interview subjects, so that ADSub13 is the same person, whether we look at survey or interview data, but this is not true for the other two courses. For example, FV13Sub09, FV14Sub09, and FVESub09 are three different people. Table A.1 provides the range of identifiers for each kind of data.

Group of Participants	Identifiers
Fluid Mechanics, Fall 2013 Survey Respondents	FM13Sub01 - 26
Fluid Mechanics Spring 2014 Survey Respondents	FM14Sub01 - 55
Flow Visualization Spring 2013 Survey Respondents	FV13Sub01 - 33
Flow Visualization Spring 2014 Survey Respondent	FV14Sub01 - 31
Fluid Mechanics Interview Participants (all from Spring 2014)	FMSub##
Flow Visualization Interview Participants (all from Spring 2014)	FVESub## - engineers FVASub## - artists
Aesthetics of Design Summer 2014, Survey and Interview Participants	ADSub01-22

Table A.1: Participant Identifiers