Encouraging the Transformative Experience in Engineering Education

ATLAS PhD Preliminary Examination

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Introduction

This document explores the significant prior work related to my dissertation research in college level engineering education. While my research will be directed toward college engineering students, it may also provide a background for related work in other STEM (science, technology, engineering, and math) disciplines, and elsewhere.

Broadly stated, the problem I seek to address is this: students often do not see how their courses connect with real situations they encounter in the workplace. In fact, beyond school, students quickly discover their knowledge is less important than what they can do with that knowledge. Making connections between concepts, pulling from multiple disciplines to solve problems, and generating new ideas are all generally more valuable than an ability to solve homework problems.

In the memoir of his childhood, neurologist and author Oliver Sacks notes that practical knowledge often far outstrips theoretical understanding in science, 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, could be fundamental to how human beings learn. Why, then, do we regularly 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, in the attempt to show students all the shortcuts, we frequently give them 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 on the same branch. How do 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.

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 good educational experiences are. My working definition of good educational experiences will draw on seminal works from John Dewey and Lev Vygotsky, as well a relatively recent thinkers such as Seymour Papert and Kevin Pugh.

In particular, Pugh’s definition of a *transformative experience* allows us to grapple with several aspects of positive educational experience at once (2011). Students who have a transformative experience (TE) will: 1) apply ideas from a course in everyday experience without being required to; 2) see everyday objects or situations differently, through the lens of the new content; and 3) value the content in a new way because it enriches everyday affective experience. Briefly put, the three hallmarks of TE are:

- Motivated Use
- Expansion of Perception
- Experiential Value

These three hallmarks, in turn, allow me to frame the different facets of this literature review in a meaningful way. In addition to exploring relevant education research, this work delves into fields from psychology including motivation, perception, emotional connections to learning, creativity, perseverance, and mindset.

Education

Dewey

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. His 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, and that 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 changes at least as great in scope, if not greater, 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 delivered in videos rather than in person are still attempts to "deliver" education; they still follow a transmission 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.

The theory of learning through experience may seem obviously better; still we find in practice many college classrooms where instructors make little effort to understand students' previous experiences and go about providing instruction with limited hands-on experiences with the material. One may point out that the college requires certain prerequisites to be completed before students begin a particular course, and that 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 wrong with problem sets, per se, 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" (1938, p. 85), which they then have difficulty applying in new situations. However, when we design courses for depth of conceptual understanding, some breadth of content is 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. These 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. Of course some students will leave their STEM majors. When this happens, we want it to be because they have located a more authentic passion, not because they are fleeing poor teaching. And they *are* switching because of poor teaching. 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. With chapters names including "The Weed-Out Process" and "The Unsupportive Culture", the study documented through 600 hours of interviews of over 400 participants the specific troubles that arise when instructors assume that lecturing and assigning more problem sets is enough.

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. 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. Brown, 1992, p.170). 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 for the serious costs of attending college. Looking at past and (potential) future experiences in the design of a course is therefore becoming more important.

Another criticism of Dewey's theory of experience is that the discovery process by the learner can lead to wrong conclusions about the world (A. Brown, 1992). I 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 them to always happen. 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).

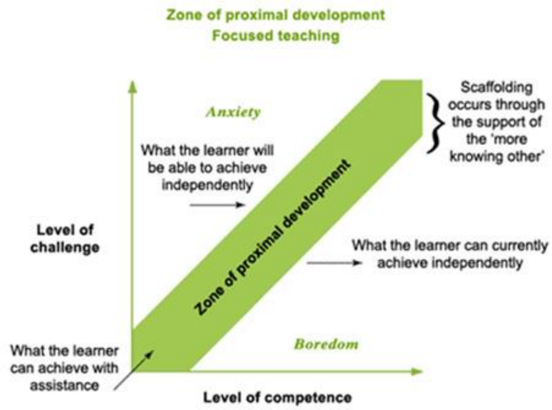
This misunderstanding of experience-based learning has persisted with strong critiques such as that by Kirschner, Sweller, & Clark (2006), who equate all forms of discovery learning with "minimal guidance" and conclude that scientists, while demanding solid evidence in their disciplines, depend on fuzzy intuition in their teaching. As we will see, 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 which are outlined by Henderson et al. (2011).

Vygotsky

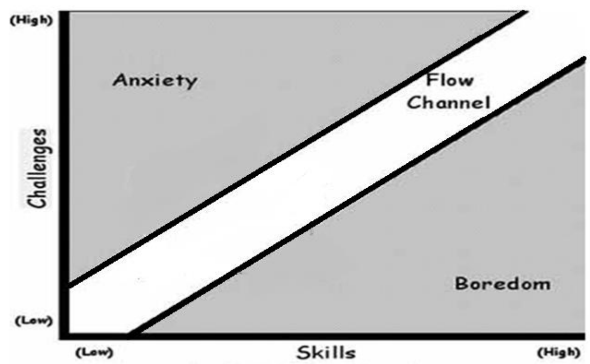
Russian psychologist Lev Vygotsky (1896-1934) wrote primarily in the 1920s and 30s, although his impact outside of Russia was delayed by politics and translation. *Thought and Language* from 1934 was not translated into English until 1962 (with revised editions appearing in 1986 and 2012), and the influential *Mind and Society* that collected previously untranslated lectures was not published until 1978. While there is a great richness to Vygotsky's work, here I want to explore three major ideas.

The first is the oft-cited *Zone of Proximal Development* (ZPD). Specifically, "it 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). In contrast, those working below their ZPD can complete tasks, but are not learning anything new, and those learners attempting tasks above their zones will find them impossible to accomplish, even with assistance. There is a 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. Yet, I do not believe Vygotsky intended this to suggest that one cannot learn alone; only that the accurate, timely measurement of the zone is accomplished this way.

Although Vygotsky does not comment directly on the learner's emotional experience in the ZPD, it can be related to idea of *flow* as defined by Hungarian-American psychologist Mihaly Csikszentmihalyi. Csikszentmihalyi focuses on a person's emotions during a task. These emotions 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 even though Csikszentmihalyi does not address flow during an overt learning task, these ideas clearly apply to learning. By examining the two concepts, we can see flow is more likely to occur in a person's ZPD. In fact, some diagrams representing both these concepts look remarkably the same:



Adapted from Hill & Crevola (unpublished)



A. M. Csikszentmihalyi (1990). Flow: The Psychology of Optimal Experience

Research of flow has expanded beyond individuals to social settings, such as teams or musical ensembles (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), which I will address in a later section.

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 (Vygotsy, 1934/2012, p. 198) [1]. Similarly, the term *scaffolding* is often used in conjunction with ZPD (even though 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, Collins, & Duguid, 1989; Podolefsky & Finkelstein, 2007). When well-done, scaffolds are eventually removed, and the learner can accomplish the task without them. When poorly done, learners find they cannot recognize the knowledge needed for a task without the scaffolding to cue them. Developing appropriate scaffolds becomes one of the major challenges to creating an effective learning environment.

[1] This also foreshadows the "2 Sigma Problem" defined 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).

Second, Vygotsky outlines how children develop language and thought – first playing with vocal sounds, then saying all verbal thoughts out loud, and eventually developing both internal and external dialogue. This closely mirrors how learners develop any new knowledge. They must first play with the ideas, then express them externally, before the concepts can be internalized. As I will discuss later, the concept of play is important to learning. Vygotsky directly compares learning a foreign language to learning scientific concepts, mediated through native language as both typically are. Vygotsky also contrasts foreign language and scientific concepts, suggesting that foreign language is more useful for a learner understanding the system of his native language. Native language is typically learned without explicit knowledge of its grammar, and when the grammar of the foreign language is learned, that knowledge can reversed. When applied to the native language, the learner then develops more advanced use of the native language by understanding its grammatical structures.

For Vygotsky this is a major difference between learning scientific concepts and learning a new language (Vygotsy, 1934/2012, p. 208). Here I believe Vygotsky's focus on language masks an important connection: that the structures learned in the study of scientific concepts *also reverse* – not to allow us advanced use of our native language, but to transform our native experiences within the physical world. Just as studying the grammar of a foreign language helps us see the structures in our native one, studying scientific concepts provides us with advanced understanding of our interactions with the world. Without this reversal, this application of knowledge to everyday experience, STEM students will learn new ideas in an isolated "dead leaf" way, and be unable to use them properly in context after having memorized a definition, a difficulty commonly noted in the PER literature (Redish, 2005). Worse, students will see a difference between the way the *course* tells them the world works and the way their *experiences* tell them it works (Redish, 2003, p. 13).

Finally, Vygotsky emphasizes the interplay between the structure of a thought and its function (Vygotsy, 1934/2012, 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 criticizes Piaget for treating these 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, I believe STEM courses are too often structured with little regard as to how the knowledge will eventually be used. 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, a difficulty we can begin to remedy by recognizing that all learning is *situated* (Wenger, 1998).

Vygotsky's research presages the 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* and learning is understood to be *situated* within that community (Lave & Wenger, 1991). Similarly, situated cognition[2] 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. (1989) 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 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.

[2] 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)

Piaget

Highly influential Swiss psychologist Jean Piaget (1896-1980) focused on the development of children, calling his epistemology *constructivism.* Piaget's constructivism 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). 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). Note that this also speaks against a transmission view of learning.

At the fourth or highest level in 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" (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", and 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.

Papert

This leads to Seymour Papert's notion of *constructionist learning*. Papert (1928-) is a South African computer scientist and educator, whose education work at the MIT Media Lab was mainly published in the 1980s and 90s. While Papert prefers to play with the notion of constructionism rather than provide an absolute definition (Papert & Harel, 1991), a working explanation of constructionism is that all knowledge is constructed in the mind, which more readily occurs when we construct something in the world.

Constructionism can fit 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 Papert[3], compares Piaget's construct*ivism* and Papert's construct*ionism* (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 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

The Physics Education Research (PER) Community

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

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

frameworks, and then systematically testing them in practice. For example, the prevalent notion of discovering students' misconceptions about physics principles, and confronting them in an attempt to change their minds, may have led to students' belief that physics was somehow not about "the real world" (McDermott, 1992). So, this "elicit, confront, resolve" tactic is giving way to acknowledgement of the students' "phenomenological primitives" or p-prims for short (Hammer, 1996). 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, 1996). 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, and a disconnect between their experiences of the real world and physics, the discipline that describes the actions of the real world.

Pugh & Collaborators

Kevin Pugh, an American educator currently at the University of Northern Colorado, draws explicitly on Dewey to define his construct *transformative experience* (TE), as defined in the introduction. This educational experience draws not only upon Dewey's connections between education and experience, but also upon Dewey's writing on art and aesthetics.

When Dewey writes of "*an* experience" he characterizes a short period of time that becomes a unit within our memory, a moment with a beginning and an end with specific, often emotional or profound meaning attached to it. Dewey describes this moment in the context of an aesthetic experience with art in the broadest sense – music, painting, theatre, etc. (Dewey, 1934). Here, I follow Kevin Pugh's interpretation of Dewey's "*an* experience" as being a transformative one, one that marks a pivotal point, after which we view the world differently in some important way.

Pugh also associates the TE with Csikszentmihalyi's flow, summarizing flow as "unity of person and activity." This is one of the ways a student's identity may be formed within a discipline; if while working in that discipline she is experiencing flow, i.e. having transformative experiences, she is more likely to strongly associate herself with that discipline. Groups that experience flow likewise form a collective identity (Sawyer, 2007, p. 48), what might be called a small-scale community of practice.

Although Dewey himself never equates powerful aesthetic experiences with educational ones, Pugh and others have described the link. "Powerful ideas lead to new ways of thinking about the world and new ways of acting on it as we put the ideas into actions.... we may conclude that ideas have the same potential as art to transform our relationship with the world" (Pugh & Girod, 2007, p. 12). Indeed, scientists have long described what they study as beautiful or mathematical proofs as elegant, and Girod, Rau, and Schepige promote drawing on the sense of the aesthetic to teach the sciences (2003). In "Science, Art, and Experience: Constructing a Science Pedagogy from Dewey's Aesthetics," Pugh and Girod combine Pugh's early explanation of TE (Pugh, 2002) and Girod's aesthetic experience, which they view as two different attempts to describe the same outcome: students experiencing Dewey's type of aesthetic experience in the context of scientific ideas. While transformative experiences are not always "aesthetic," there is often a sense of wonder or an appreciation of balance in these experiences, even in the stereotypically "nuts and bolts" world of engineering.

To reiterate, Pugh characterizes TE as 1) involving motivated use of content (outside the classroom); 2) expanding of perception of the content or ideas to outside the classroom, and 3) valuing the experience, or having positive affective toward the material (Pugh, 2011).

On neuroscience and learning

This section highlights a few larger concepts that neuroscience has contributed to my understanding of learning. The first is that our working memories are remarkably small. The rule of thumb is that we can hold 7±2 items in our working memories at one time (Kirschner et al., 2006). We greatly optimize the use of those seven items if we can chunk information or actions in our minds and draw on items already in long term memory. For example, an experienced mathematician will perform several algebraic steps in her mind when working through a problem that the more novice student will feel the need to write out. An experienced painter may unconsciously mix pigments to get the exact shade he desires, while the beginner will have to experiment or consult a reference. This kind of automatic action by experts is colloquially called “bottom up” thinking because the activity is largely unconscious. The working memory, directly accessing the prefrontal cortex, is then able to do the “top down” thinking we associate with conscious thought (Goleman, 2013).

Whenever we activate a memory, our synapses are open to the editing of that memory – this includes adding details, connecting ideas, or, oddly enough, forgetting a particular memory (Bastin et al., 2012). When we help learners connect new ideas to old ones, we have the opportunity to reinforce or adjust previously held ideas, which in turn makes it easier for learners to remember the new ideas. The new information is more easily built into their brains when it has an existing network of synapses with which to connect.

Educators find that a concept “will continually evolve with each new occasion of use, because new situations, negotiations, and activities inevitably recast it in a new, more densely textured form”(J. S. Brown et al., 1989). Thus, these two theories, education-as-experience and constructionism, are not only analogies of how we develop what we know.

They relate very closely, biologically, to how we build what we know.

Psychology

Motivation

In Pugh’s characterization of TE, the first item is motivated use, but what, precisely is motivation? 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. In other words, 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 is most certainly 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 also address what "sustains" our activity (Higgins, 2012, p. 232). Understanding motivation theory can help us to create better environments for students, so that they will see the value in staying.

Current education models generally motivate students by awarding grades; conversely, students figure out what is important through this process. The implication is that we value 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." Yet, despite students' clear habituation to this system, we need to break away from this strictly carrot-and-stick approach to motivation. Maladaptive behaviors, such as avoiding courses or instructors perceived to be "too hard" or cheating on exams, 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. There is not a clear link between doing well in formal learning settings and doing well in professional settings. This weakens the perception of reward. The hedonic principle (carrot-and-stick approach) to understanding motivation is both reductive and lacking 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.

Perhaps we can gain a clearer understanding of motivation by considering our neurobiology. 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 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. 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. Professors do not have to focus on being entertaining so that students will like their fields, a common criticism in attempts to reform courses. They can aim instead for giving the students reasons to want to learn 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 here, education (Vansteenkiste & Simons, 2004).

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 take 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,[4] 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 as defined under 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. In fact, 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. What is going on here?

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 he were being paid significantly less than

[4] See Evergreen State College, Olympia, WA. (http://evergreen.edu) Also, University of California, Santa Cruz, from 1965 to 1997.

his co-workers for the same sort of work, he would no longer perceive his pay as *fitting* the task, and be de-motivated by thinking about his paycheck. This demotivation also occurs if the employee learns that those workers doing significantly less work are rewarded at the same level he 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 says we are more motivated when the action, our reasons for doing the action, and means of performing the action are aligned. 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 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 (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 most cogent 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," and 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, Grit, Mindset, and Play

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 (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. 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. Robinson notes that creative ideas need only be original to the thinker, not to all of humanity.

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 before[5], constructing new thoughts. Sometimes these incremental changes are failures, with each new attempt an iteration.

[5] Neurobiology also informs this idea, since neurons that "fire together wire together" in what is known as Hebbian learning (Aisa, Mingus, & O'Reilly, 2008). Creativity requires our brains to literally wire together new neurons.

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.” 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 clear that a person’s belief about his capabilities plays 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 in some fashion (Kennedy-Moore & Lowenthal, 2011).

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. "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 a STEM degree.

How can we foster the growth mindset? The typical way engineering courses are scheduled does not allow for the kind of iteration that supports growth. STEM 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 actual comprehension.

There are practices, backed by research, that stretch imagination and creativity, which anyone can use to increase their likelihood of having useful, original ideas. Most of these techniques require a cycle of immersion in a task, follow by reflection (harkening back to both 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. 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). Yet play is essential to experiencing new ideas, fully understanding them 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 fun or playful. This leads to a conundrum. If students perceive their study as only serious and attempts at injecting fun destroys the "fit", how can we encourage students toward motivated use of their new knowledge?

Perception

Pugh's second characteristic of TE is expansion of perception. Perception is how our senses tell us about the world and our state within it, using our nervous system. That is not to say that we perceive everything our nervous system does, since our perception of previously unnoticed activity like our heart rate usually occurs only when there have been important adjustments to those automatic responses (Saper, 2002). And just like our heart rate does not catch our attention until it changes significantly in some way, many details of our everyday experience do not stand out in our perception until we learn that they are important to notice. This sort of perception can be learned, and it is context-specific. For example, experienced radiologists who quickly and accurately find potential cancer cells in medical images were no better than lay people at finding target items in a non-medical image (Nodine & Krupinski, 1998). Once again, we find that learning is *situated*. One challenge of reaching Pugh's "expansion of perception" is making the leap of "seeing" certain ideas previously situated in the classroom to "seeing" them outside the classroom.

Like the radiologists, experts in other fields learn which aspects of a problem they must attend to, and which they can safely ignore when working those problems. Just as one attribute of flow is that distractions are excluded from consciousness, we might also say that the experts can achieve flow more easily because they know which details are not essential to their work. Experts maximize the use of those 7±2 items of working memory. 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* and then have to dig out a bird book to further identify a *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 even able to identify at that level at all); the expert can often go directly to that level.

Another example of categorization is the grouping of physics problems. Chi, Fletovich, and Glaser 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). Although more abstract than the bird-watcher example, this example also shows how experts' perceptions are developed in particular ways. Students, as novices, often do not perceive which details in the problems are most important, and are 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 naturally pay more attention to getting that number right than to the acquisition of deeper conceptual understanding. Developing that conceptual perception does not come "for free" as Redish notes, but rather is part of a "hidden curriculum" that instructors must make explicit and must find ways to assess (Redish, 2003). Only then will students' learning actually align with the goals of the course. Only then will their perceptions shift from those of a novice to those of an expert.

However, this does not get us to Pugh's expansion of perception. Pugh highlights in his work multiple cases where students undergo expanded perception based upon their classroom learning, such as a student noticing force pairs in an action movie car crash (Pugh, 2004). In my own work, I interviewed a student interested in both environmental studies and fluid dynamics who had recently noticed the plume from a smoke stack flattening instead of rising due to a temperature inversion. He was encouraged and excited by the realization that his studies had come together to expand his perception of the world. How do we encourage this bridging of ideas from classroom into the outside world?

Affective Value

The final characteristic of TE is experiential value, that is, when students use their new knowledge outside the classroom and when their perception is expanded by that knowledge, do they assign a positive emotional (or affective) value to that experience? Heightened perception can be negative, as anyone who has gotten sick of popular song will report. Suddenly the song is on the radio, in a commercial, over the loud speakers at the store, and it is annoying. Nevertheless, we can hope that most students, when experiencing expanded perception, find it fascinating, not irritating, as my interviewee did.

Affect is a messy area to study, and there is considerable debate in psychology over major concepts, and even terminology. Are there basic, identifiable emotions across all humans (Ekman, 1992) or not (LeDoux, 2012)? Do our physical responses generate our emotions (James, 1884; Niedenthal, 2007), an idea called embodied cognition, or is that a relatively small piece of the puzzle? There are more questions than answers at this point, perhaps due to the early focus on dispassionate cognitive functions. For example, decision-making was studied in its non-emotional forms first. However, for any decision-making theory to have consistent predictive power, it needed to take into account our emotions. The two ways of thinking are colloquially referred to as *hot cognition* (emotions) and *cold cognition* (rationality). Nobel Laureate Daniel Kahneman makes a similar distinction, using the terms *fast thinking* and *slow thinking* (2013). Emotional reactions to situations are indeed faster than the time required to sort through information. Emotions evolved to help us survive, according to evolutionary psychologists (Cosmides & Tooby, 2000). Some of our native emotional reactions are no longer helpful, but this sense of gut-level reaction can be improved or trained, sometimes in subliminal ways (Pessiglione et al., 2008). So, what is a student's reaction to recognizing some STEM concept out in the world? Is her gut reaction to say, wow, this is cool? Or yuck, how annoying?

Here I want to bring the word aesthetic back into mind. The TE is not about noticing great scientific ideas in everyday life mechanistically or rationally. I contend that instructors make positive affective association more likely when we highlight the beauty, balance, or elegance of the concepts we handle in our STEM disciplines. We make those associations more likely when we freely show our own sense of wonder or delight with the ideas as we teach them in class, and deliberately share anecdotes of our own TEs.

Analysis

John Dewey wrote that one could not reform education by rejecting out of hand what one did not like about the current system. Just because one system of organization seemed to stifle learners' creativity did not mean that chaos should reign. Similarly, he was a proponent of understanding where students' knowledge, skills, and abilities (KSAs) were at the beginning of an educational unit, so that we could better understand whether the "treatment" was effective. Here are the roots of fruitful assessment and research in education.

In psychometrics, there is a fundamental division between attempting to measure people's behavior and gauging their attitudes. Measuring actions is simpler, but for the purposes of my work, the latter is more important. Given two students who transfer out of STEM majors, there is an important difference between the student who is switching to a newly discovered passion and a student fleeing a disappointing major. The first we would encourage to embark on that newly discovered passion. The latter we would interview to learn the reasons for his or her disappointment. Given the formative nature of education, there will be a spectrum of attitudes about why students choose their majors, why they persist in them, or why they switch. We want to encourage students' well-informed choices about their majors, which presumably requires understanding the disciplines in an authentic way, a way that is not best represented by the classroom. This is why creating coursework that makes the transformative experience more likely to occur to seems so vital to me to improving higher education.

A Preliminary Look at My Research Design

While keeping all three characteristics of TE in mind, my work will focus on the expansion of perception. Survey responses to the Flow Visualization course, MCEN 4151, taught by Prof. Hertzberg, indicate an expansion of perception for concepts related to fluid physics. One part of my research will examine survey data taken from this course since 2009. These survey data will be supplemented by before-and-after interviews with students. Survey and interview data from the Flow Visualization course will be examined alongside data from Fluid Mechanics (MCEN 3021), and two other elective courses, Sustainable Energy (MCEN 4228-002) and Aesthetics of Design (MCEN 4228-001). The survey data will be examined using a polytomous Rasch Model, based in Item Response Theory (M. Wilson, 2005). Statistical tests, such as the Wilcoxon Signed Ranks test, will be used for the groups of interval data from the surveys and coded interviews.

I will be following Mark Wilson's approach to Item Response Theory, which views measuring as an act that first requires defining the construct, or concept of interest. The construct is theorized to exist before we attempt to measure it. The *construct map* is the outline of the "distinguishable qualitative levels" that can be mapped onto the continuous construct. By defining these levels, we can design (or in this case, refine) an instrument, usually containing multiple items, that measures subjects on that construct. Designing items that accurately represent a subject's level of the construct requires consideration of confounding factors, as well as validation testing.

To further define the expansion of perception often noted by students in Flow Visualization, Prof. Hertzberg and I are working on an experiment with Prof. Tim Curran's group in the Psychology department to establish a way to measure Visual Expertise in abstract concepts from fluid physics.

I am also considering other courses that may be candidates for encouraging transformative experiences including, new courses in the Idea Forge at CU Boulder and the inWorks at CU Denver.

I would also like to characterize courses that discourage transformative experiences by examining the data from the College about which courses are most often dropped and/or coincide with students leaving the College without completing a degree. Another method of locating and examining these courses may come from interviewing the Engineering Fellows, who are instructed to select "at-risk" courses for which to provide supplemental instruction. They have thrived in these difficult classes, and may be able to offer some perspective about whether they are "weed out" courses, and if so, what aspects of the courses make them so.

We cannot force students to have transformative experiences, any more than we can force ourselves to have creative thoughts. However, just as certain practices of mind can encourage the creative process, I contend we can develop pedagogical practices to encourage our students to have an insightful transformative experience.

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