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Nurturing Creative Processes and Attitudes in Introductory Materials Science

Abstract

We educators face a pressing need for our courses and curricula to turn out more creative people. Unfortunately, most of our undergraduate engineering environments provide few opportunities for students to engage in creative processes. Engineering instructors habitually design courses that are loaded with instructor controls. Faculty tell students what to learn, how to learn it, when to learn it, and why they should care about learning it. The results are often low student intrinsic motivation, lack of individual internalization of learning goals, and limited learner engagement in higher-level cognitive and metacognitive processes, all of which may lead to decreased creativity. One approach to unleashing students' creative potential may lie in nurturing their self-directed learning capacities. Creativity research tells us that individual autonomy is a core characteristic of creative people, and that achieving creative potential may require development of a strong sense of self-determination. This paper describes an introductory materials science course built on the premise that student choice and control facilitate engagement, self-motivation, and creative approaches to learning. The course design leverages existing educational research that suggests strong correlations between self-determination and creativity. By providing students with increasing levels of autonomy – and corresponding increases in creative opportunity – throughout the semester, the project-based learning experiences enable students to connect materials science topics to personal interests and contexts. Students report that the course contributes positively to their creative thinking, and they emphasize the benefits of freedom in choosing topics and learning strategies.

Introduction

Imagine yourself as a first-semester sophomore, entering the classroom on the first day of your introductory materials science course. For you, this course represents one of the last foundational engineering courses you must complete before you start your major course sequence. Viewed another way, this course is your gateway to the "real" engineering courses. You are feeling excited but a bit nervous, anticipating what is sure to be a tough few years of engineering education. You wonder about the students around you, how they did in the "weed out" courses, how smart they are, how far along in the program they may be.

Your instructor enters, and all the whispers in the room quickly fall to silence. The instructor is fairly new to the mechanical engineering department, so you have not heard much about his teaching style. He is younger than you expected, and rumor has it that he comes from the nanotech industry. You anticipate that this will make for a more enjoyable course, or at least a few more cutting-edge examples.

The instructor passes out the course syllabus, and begins the expected first-day drill. He tells you that the course provides an introduction to materials science. No surprise. He tells you that you will learn a lot, since the course covers metals, polymers, ceramics, composites, and semiconductors, including atomic structure and bonding, crystallography, defects, diffusion, dislocations, slip systems, phase diagrams, phase equilibria, phase transformations, and a host of other topics. The course format is lecture-based, but he will attempt to provide some examples of practical applications from his industrial experience, and he encourages students to ask "serious" questions during the three weekly, one-hour lectures.

Your attention begins to wane, but his mention of grades re-awakens your interest. Your final grade in the course is made up of 20 percent from homework, 40 percent from exams, 20 percent from the final exam, and 10 percent from class attendance. Homework up to three days late will be accepted, but points will be deducted from assignments that are turned in late. Working or studying in teams is encouraged. However, all homework problems must be worked out and submitted individually. There will be three tests and a final exam. Each test will cover the material since the previous test, and the final exam will be cumulative. All exams will be closed book. No make-up tests will be given. Class attendance is mandatory, and your instructor will take attendance randomly during the semester. After the first absence, each subsequent missed class will result in a loss of one percentage point from the final grade. The total possible points that may be lost due to missing class is 10 – the equivalent of a letter grade.

Textbook readings will be assigned each day, and you are supposed to complete the readings before the following class period. The instructor seems to sense the collective, internal moans regarding the reading assignments, so he continues with a point of emphasis that seems to fall somewhere between plea and demand. "It is *extremely* important that you read the textbook", he notes. "It is very difficult for you to understand the concepts and succeed in this class without reading the text and attending all lectures."

As he sets the syllabus aside, the instructor expresses his desire for the class to work hard and enjoy the semester of materials science. He then pauses for a moment. "But above all else," he notes, "I would like you use this course to become a more creative, more innovative engineer."

Background

College instructors have been struggling with a lack of creative skill development in their students for many decades. Creativity is by no means a new topic in teaching and learning, but it is one of growing significance in engineering educational discourse.[1,2,3] In 1965, Maslow argued that creative people are a "necessity for any viable political, social, economic system" that wishes to avoid obsolescence. Maslow targeted engineering education in 1971, noting that "we must teach and train engineers not in the old and standard sense," but in a manner that enables them to confront novelty, to improvise, and to gain comfort with change.[4] The National Academies recently echoed these decades-old sentiments and included creativity as a necessary attribute of the "technically proficient engineers who are broadly educated, see themselves as global citizens, can be leaders in business and public service, and who are ethically grounded."[3] The National Academies describe creativity as a high but attainable bar in engineering education, and they emphasize that

> Creativity (invention, innovation, thinking outside the box, art) is an indispensable quality for engineering, and given the growing scope of the challenges ahead and the complexity and diversity of the technologies of the 21st century, creativity will grow in importance.[2]

As a result of these recent visions and renewed expectations for technical education, there is mounting pressure on engineering programs to turn out more creative graduates who are equipped to tackle complex 21st century challenges. Today's engineering educators express increasing concern for students' development of creative capacities, but many of these same educators continue to adopt controlling classroom approaches that provide little opportunity for divergent thinking.

One problem engineering educators face is the traditional thinking about course design and student-faculty interactions that pervades technical programs. Carl Rogers argues in *Freedom to Learn* that many college educators implicitly assume that "The student cannot be trusted to pursue his own scientific and professional learning" and "Creative scientists develop from passive learners".[5] Despite a desperate need for increased creative opportunities, engineering students are rarely provided with freedom to explore new spaces or concepts. Instructors routinely embrace teaching tactics that outline *what* exactly students need to learn, *how* exactly students need to learn it, *when* the learning must start and end, and *why* students should care about learning it. Engineering educators are intentional and decisive, to be sure. Instructors carefully analyze learning situations until they formulate a precise understanding of students needs, they present well-defined learning goals and detailed strategies, they thoughtfully craft assignments, and they provide continual supervision and evaluation. One must wonder, however, if this attitude among faculty will effectively bolster creative thinking among our undergraduate populations. If creativity is a desired output, students must take a more active role in designing their own education, and instructors must shift their thinking toward imaginative, playful, inspired approaches.[6] As Einstein notes,

> It is in fact nothing short of a miracle that the modern methods of instruction have not yet entirely strangled the holy curiosity of inquiry; for this delicate little plant, aside from stimulation, stands mainly in need of freedom; without this it goes to wrack and ruin without fail. It is a very grave mistake to think that the enjoyment of seeing and searching can be promoted by means of coercion and a sense of duty.

It is high time for all engineering educators to consider how creative thinking fits into their courses and curricula. Instructors must take seriously questions such as: Does extensive structuring of learning provide security but drive students further from the unknown or innovative? Are expectations for student creativity, originality, and curiosity reasonable in overly constrained learning environments? Are engineering educators doing as Rogers suggests – "placing our bets for the future on the student who absorbs and then gives back on examinations"?[5] Can engineering educators relax their obsession with control to an extent that they promote individual creative development?

The impetus for this article was not the discovery of a perfect solution to engineering education's creativity problems. Rather, it was consideration of an interesting and somewhat unexpected student response in a project-based introductory materials science course. The course was intentionally designed as an engaging, hands-on environment that supports student *autonomy* and promote student development of skills in *self-directed learning*. As such, high levels of motivation, engagement, and interest in the topic and assignments were expected. What was not anticipated, however, was the extent to which the materials science course appears to promote students' *creative thinking*. This article represents a first attempt at understanding the connections between autonomy and creativity in this particular classroom context. The aim here is not to review the abundant body of literature that exists on the nature and nurture of creativity. Rather, this article seeks to (1) highlight a marked failure in traditional engineering educational approaches to offer learning environments that foster creativity, (2) emphasize the importance of autonomy in the development of creativity, (3) provide an example of an introductory-level materials science course that leverages student choice and control to promote engagement, self-motivation, and creative thinking, and (4) encourage engineering educators to consider curriculum design approaches that foster student creativity.

Conceptualizations of Creativity

The development of creative skills, like most areas of broad competency development, involves a complex interplay among a multitude of factors. Early approaches to creativity focused on individual intrinsic traits such as personality and intelligence, but more recent conceptualizations have expanded the creativity developmental frameworks to include factors well beyond those intrinsic to individuals. Gardner, for example, describes the cognitive, behavioral, motivational, and social-psychological issues at the individual level, but he also highlights the significance of interactions among individuals, domains, and fields in the development of creative work.[7] Supportive and accepting environments, as well as developmental time, are important themes in Gardner's creativity framework. Amabile approaches creativity from a similar social-psychological perspective that integrates personal characteristics, cognitive abilities, and social environments; and she proposes that anyone with normal cognitive abilities can be creative in some endeavor. In her componential conceptualization for creativity, Amabile outlines a variety of domain-relevant skills (e.g., relevant knowledge), creativity-relevant skills (e.g., idea generation skills), and task motivations (e.g., attitudes toward the task and absence of extrinsic constraints).[8] She emphasizes the importance of "creative situations" – circumstances conducive to creative development – that arise when the social and environmental contexts are synergistic with individual motivations and interests. Csikszentmihalyi captures the personal and environmental aspects of creativity well in his statement that, "creativity does not happen inside people's heads, but in the interaction between a person's thoughts and a sociocultural context."[9]

Conceptualizations of Autonomy

Deci and Ryan define autonomy as "volition – the organismic desire to self-organize experience and behavior and to have activity be concordant with one's integrated sense of self."[10] In his work in self-directed and lifelong learning, Candy describes autonomous individuals as those who are able to conceive of goals, exercise freedom of choice in thought and action, resist inward or outward constraints, self-reflect, fearlessly implement plans of action, exercise self-mastery, and conceive of themselves as autonomous.[11] Educational psychology research shows that autonomy is a critical component of self-motivation in learning, and that autonomy is necessary for individual internalization of learning goals. When students feel a sense of freedom, choice, control, ownership, and volition, they demonstrate more intrinsic motivation, improved self-regulation, and healthier psychological development.[10,12,13]

Autonomy is considered by many to be a core characteristic of creative people (see, e.g., Barron and Harrington[14] and MacKinnon[15]). Recent creativity research affirms a positive correlation between the extent to which individuals are self-determined, and the extent to which they are creative.[16] Some researchers posit that autonomy-oriented people possess a natural resistance to outside pressure that may restrict creative expression or development,[8] and that self-directed, self-determined people are more apt to overcome social and environmental norms and constraints in order to exercise creativity. Autonomy and support emerged as significant themes in a recent qualitative study of expert creative engineers who were asked about their creative experiences and processes.[17] In this work, professional engineers expressed a desire for freedom, trust, and support for risk-taking in their industrial settings. Although investigations of autonomy-creativity linkages do not suggest that provision of autonomy necessarily results in creative output among undergraduate students, the research may indicate that if engineering students are allowed increased autonomy and supported in self-directed efforts, creative expression will follow.

Autonomy and Creativity in Engineering Programs

The Importance of Environment

Given the correlation between personal autonomy and creativity, should engineering educators simply run out and find the most autonomy-oriented individuals, and attempt to convince them to pursue a glorious career in engineering? Perhaps. Engineering faculty could work with college admission teams to devise strategies to target students who have creative traits or experience in creative processes, effectively boosting the percentage of creative personalities in their classrooms. Attracting individuals who are more oriented toward or practiced in creativity may spark creative development in our programs, but it could also serve to stifle further development of these creative individuals. Without creativity-promoting learning environments in engineering, even those students deemed sufficiently creative at the start of their college career are unlikely to experience significant growth.

Rather than changing the student population within engineering programs, the transformation of engineering classrooms probably provides a more viable strategy for instructors who already work within a particular educational setting. Engineering educators typically have considerable control over course design, including attributes of the social and environmental contexts within which students work. Modification of the work climate can positively influence individuals' sense of autonomy, and creative thinking and behavior.[18] With effective design and careful consideration of situational factors, the undergraduate engineering classroom can become a setting in which creativity flourishes.

Creativity…Don't Design Courses Take Care of That?

Some engineering educators may presume that individual development of creative capacities takes place in the engineering design courses, and perhaps in liberal arts courses required as part of students' general education. Design courses, after all, can provide learning experiences in which student processes culminate in tangible, created products; and writing, music, dance, and art courses offer similar production of created works. Contributing to the idea that design courses are *the* place for creativity is the growing body of educational research on students' creative skill development in design settings. Design courses often serve as the focal piece for engineering studies of creativity, and engineering instructors have achieved good success with a variety of approaches to creativity. Lewis suggests that design projects are "ideal for exposing [students] to the creative process", and he emphasizes that techniques for flexible and divergent thinking can be taught through the use of open-ended puzzles and problems.[19] Other engineers have examined the role of tools, techniques, or special training modules in enhancing creative skill development. These "toolkit" approaches argue that instructors cannot assume that students will develop creative thinking implicitly in their design courses, but that formal training in the use of creativity enhancing exercises (e.g., lateral thinking, brainstorming, association, adaptation, and first-hand experiences in problem-solving) are necessary for gains in creative performance.[20,21] Hands-on design projects are commonly viewed as an excellent vehicle for the encouragement of creativity and innovation in engineers.[22]

It is clear that design courses can provide opportunities for creative skill development. Oftentimes, however, creativity in the context of engineering design necessitates production of a physical artifact that may be evaluated by an expert observer. Should engineering students' creative expression be limited to the handful of courses labeled as "design" that culminate in the production of physical objects? Surely, this need not be the case.

A broader look at the creativity literature provides a blessing for those who operate outside of the design realm. Maslow, in his studies of self-actualizing people, argues that creativeness is an attribute of the psychologically healthy person, "a fundamental characteristic of common human nature – a potentiality given to all human beings on earth."[23] Maslow points out that there are a multitude of determinants of creativeness, but he emphasizes that anything that leads to more holistic human growth could spark increased creativity in every aspect of life.[24] Rather than a focus on the created *product*, Maslow encourages consideration of the creative *process*, the creative *attitude*, and the creative *person*. Amabile's creativity work supports this broader view that "products" can include "any observable outcome or response".[8]

Acceptance of the broader creativity definition implies that *everyone* can play a role in its advancement. This concept of distributed creative skill development has gained some traction in the engineering educational realm. Over 30 years ago, Gawain went so far as to suggest that *all* engineering educators may play a part in facilitating students' creative development, and he provided specific "corrective actions" for accomplishing this:

1. Introduce into your courses a modest proportion of homework problems, term projects and so on, oriented toward synthesis and design objectives rather than just toward analytical aims. This step can be taken immediately in nearly every course regardless of academic level.

2. If students become deeply involved in a creative way with some of these projects, grant them the extra time needed for execution by excusing them where feasible from some of the routine analytical requirements of the course. Grant compensatory credit for such work. Accept design reports, oral and written, if presented in true professional style, in lieu of certain conventional course work and examinations.[25]

Craft builds on the broad creativity definition in her recent examination of creativity in education, and distinguishes among the "everyday creativity" of Maslow, the "extraordinary creativity" of the likes of Einstein, and "localized creativity" that lies between the two extremes.[26] Craft argues that creativity is relevant across the entire curriculum but manifest distinctly in different fields – an approach that should spark some excitement among those who may feel pressure to the responsibility for students' creative development to the design instructors. With improved understanding and a little imagination (or creativity, if you will), it is apparent that all educators may establish course environments that promote development in the localized creative realm.

Introductory Materials Science Course Student Experience

This section explores some of the environmental aspects of creativity by examining the design of and student responses in an introductory materials science course. The classroom climate, learning tasks, and student responses in this particular setting are analyzed through the lens of social-psychological conceptualizations of creativity.

The introductory materials science course provides a project-based learning experience that is autonomy-supportive and rich in exploratory opportunities. The course is divided into three phases that last approximately five weeks each. Each phase is organized around a hands-on project. Students gain conceptual understanding of materials science primarily *through the project work*, and assigned readings and problem sets in the first two projects enable connections to supporting materials science theory. Given a list of project constraints and broad learning goals, students select the problem to be investigated in each project. From a nearly infinite array of potential paths, students create an analytical plan to study materials-related aspects of a technology, topic, or product of their own choosing. The projects provide for gradually decreasing instructor control and gradually increasing student discretion and responsibility.

Project 1: Exploring Materials in Everyday Products

On the first day of their introductory materials science class, students enter a hybrid lab-classroom space that was designed to facilitate project-based learning. Upon entering the room, students immediately notice an enormous pile of common, everyday products stacked high on the lab benches. From the look of this collection of stuff, it appears as if a shopper with rather non-discriminating taste has raided the local Home Depot, Target, Toys-R-Us, and Dick's Sporting Goods, and delivered items from the clearance shelves to the materials lab. The selection of products varies by semester, but in any given course, students may see a suitcase, shower curtain, skateboard, a hedge trimmer, rope, work gloves, hammers, Barbie Dream Car, curling irons, toaster, a bicycle helmet, etc. The products are not expensive – the average cost of the five-week project is about $20 per team.

Students gain an immediate sense of the self-directed style of the course. Prior to any discussion of the course syllabus, grading, or exams, students begin their project work. They read a brief project description, examine the collection of products, and think about what they may want to study in the first few weeks of materials science. The instructor facilitates the creation of project teams based on common or similar individual interests in the products. Students' choices in *what* product they will study and, to some extent, the people with whom they will work, represent the first acts of autonomy in the course. Their next assigned task – determining *how* they will investigate their chosen object – provides a learning scenario that lies at the intersection of autonomy and creativity. Students must find ways to determine *what* materials are used in their object, *what* properties these materials exhibit, and *why* these properties are important for the particular application. Instructors provide a quick lab tour and a list of instrumentation, and students are free to try any type of property testing or analytical technique that they think will provide interesting or useful data. The selection of project strategies rests solely in the hands of the students. They decide which experiments to run, what type of data to collect, how to analyze the data, how to synthesize all of their experimental data with underlying materials science theory in the practical context of their selected product. As they strive for understanding of their materials system, students leverage many different resources, including textbooks, reference books in the lab or library, electronic books, their peers and instructors, other faculty experts, and external contacts. At the end of the project, students present their findings in posters, the content and design of which is left to each team.

A common technical learning goal of *connecting structure and composition to properties and performance* ensures that students develop their understanding of materials science concepts. The manner in which their materials science knowledge develops, however, depends on the selected object and particular project paths the teams choose to follow. Table I provides examples of several project topics from the spring 2008 materials science class, as well as a brief description of the teams' investigative approaches. For each project, students must decide what types of data are relevant to their investigation, and which analytical approaches will provide for these data. When necessary, students must devise new means of analysis, or develop new setups for their testing. Throughout their investigation, students must decide when to push forward in their chosen direction, and when to cut their losses and change direction. Reflection on choices, approaches, and interactions is a critical component of the learning process, and all students complete written self-reflections for teaming and lifelong learning competencies at the conclusion of the project.

Project 2: Exploring Metal Alloys and Processing Techniques

The second project is similar in many ways to the first. As with Project 1, students design a set of experiments to explore structure-property connections in material systems. Rather than digging through a pile of common objects, however, students generate project ideas based on interesting alloys and the processing techniques used to create metallic products. After some thinking and class discussion of the various metals and alloys they know from historical or modern-day applications, students propose their project ideas, and teams select viable projects based on shared interests and pragmatic considerations such as available equipment, time, and budget. Example projects from the spring 2008 materials course include:

- Permanent die versus investment casting of zinc alloys,
- Anodization and age hardening of aluminum alloys,
- Forging and heat treatment of low alloy steel,
- Surface powder sintering on titanium alloys for implants, and
- Solid-state diffusion in copper-zinc alloys.

The project topics vary widely from semester to semester. Students in previous offerings of the course explored copper smelting, hot- and cold-forging of bronze, welding of aluminum alloys, wire drawing of silver and copper, heat treating of titanium alloys, sintering of copper powder metals, and solidification of lead free solders.

The primary materials science learning objective for the second project is for students to develop an understanding of the effects of processing on material microstructure, properties, and performance. All students study binary phase diagrams, solid-state phase transformations, strengthening mechanisms, thermal processing, mechanical processing, and applications of metallic materials. All students design experiments and use modern laboratory equipment to answer a question of technical significance for a particular application. All students gain insights into the control, modification, and prediction of material properties and microstructure. All students learn to identify the roles that processing may play in determining the usefulness of a material in a practical context. Each project team, however, identifies its own goals and questions, creates its own learning strategies, and designs its own experimental plan. As with the first project, students complete written self-reflections at the conclusion of the second project.

Table 1. Example analytical approaches from Project 1 teams in the introductory materials science course.

Object	Experiments	Approach
Nalgene bottle	• Impact testing • Tension testing • Hardness testing • Differential scanning calorimetry (DSC) • Thermogravimetric analysis (TGA) • Fourier transform infrared spectrometry (FTIR)	The Nalgene bottle team tested claims on the bottle label that the product was suitable for "Extreme Adventures". They used FTIR to validate the "Made with Polycarbonate" material claim, they used impact and tensile testing to evaluate the "Extremely Durable" claim, they compared the hardness of the bottle to the hardness of rocks, and they verified the "Withstands 135°C to 135°C" claim by DSC and TGA thermal analyses. The team explained observed behaviors using researched information on polycarbonate's structure, and they verified all property measurements with reference values from the literature.
Raincoat	• Tension testing • FTIR • TGA • Scanning electron microscopy (SEM) • Chemical resistance • UV resistance • Surface tension	The raincoat team created experiments based on a fictional narrative for Timmy, an "average hyper and happy child, a target consumer for the brightly-colored jacket that we chose." Their tests represented possible situations the raincoat could be subjected to at the hands of a child: a dog tugging on the sleeve (tension), water resistance (surface tension), sunlight exposure (UV), and household chemical spills. All properties were explained using knowledge of the PVC polymer structure and polymer additives (e.g., plasticizers, UV stabilizers).
Hammers	• Flexural testing • FTIR • X-ray fluorescence (XRF) • Impact testing • Vibration testing • Optical microscopic analysis of a polished and etched cross section • Hardness testing	The hammer team compared the materials and properties of three different hammers (wood, fiberglass composite, and metal handles). The team used FTIR to identify the polymers used in the handles and grips, and XRF to determine the hammer head alloy composition. They tested marketing claims such as "anti-vibe" using a custom accelerometer setup on the impact tester that enabled comparison of vibrational responses of the three handle materials. The team measured flexural strength and stiffness of the handles, and explained different values based on the structure and bonding in the wood, composite, and steel. They explained the low hardness of the rubber grip based on the thermoplastic elastomer's molecular composition and structure. The team also determined that the hammer head had a martensitic microstructure, and they researched steel transformations to explain the high hardness values. Finally, the hammer team researched reference values for all of their material properties.

Project 3: Exploring Modern Materials

Students conclude the course with a study of modern materials. For Project 3, each project team identifies a materials science topic of modern technological significance, and explores this topic through a self-designed program of research and laboratory experimentation. By this point of the semester, the level of autonomy is extremely high; students have virtually free reign over the course. In addition to selecting their project topic, defining learning goals or research questions, and designing their project plan and experimental processes, students also acquire their own materials, and identify supporting information resources. The deliverable for this project is flexible, as long as students carry out rigorous experimental and contextual research that addresses a significant learning goal or question. Each project group uses classroom and out-of-class time as they see fit, and there is no competition between project time and traditional content delivery in this final phase of the course.

Students seem to take full advantage of the reduced constraints and increasing choice afforded them during Project 3. It is clear that this phase of the course provides for the greatest intrinsic motivation and interest levels, but also the highest probability of unexpected results, inexplicable data, and student uncertainty and frustration. Most students recognize the control and responsibility they have over the learning process, and they seem to accept the trade-offs between uncertainty and autonomy.

The generation of creative ideas and use of imaginative processes reach a peak in Project 3. Students in the spring 2008 section of materials science suggested over 30 project ideas and topics, including carbon nanotubes, modern resistor and capacitor materials, degradation of wet suit materials, organic LED synthesis, superconductor synthesis, water filtering materials for use in developing countries, shape-memory alloys, negative refractive index materials, ferrofluids, lead to gold alchemy, eco-friendly materials for sustainable design, shape deposition manufacturing, using lightning to turn crystals to glass, conductive polymer synthesis, material properties of paint, self-healing polymers, optical properties of butterfly wings, analysis of gecko feet, recycling of plastic bottles, making recycled paper, synthetic core instrument strings, turning biomaterials into glass, optical and material properties of colored glasses, 3D tissue culture scaffolds, abalone shell, bamboo, synthetic core instrument strings, Aerogel, wood-glue composites, controllable opacity materials, Corelle dinnerware, polyester fabrics, bioplastics, and nylon synthesis. With a little help from the instructor, students formed six project teams based on shared interests. Each team identified research questions and goals, designed and implemented their own set of experiments, found their own resources, and specified appropriate deliverables.

Throughout the semester, the instructor offers students a variety of learning supports. Early in the semester, the instructor provides laboratory training and assistance with experiments, assigned materials readings and problems relevant to the project work, opportunities for informal and formal teaming feedback, online and library resources, informal classroom feedback sessions, on-demand lectures to support project work, detailed rubrics for the formal assessments, and detailed feedback on project deliverables. As the semester progresses, these supports are loosened or removed, facilitating students' transitions from more structured learning to autonomous learning.

Results and Discussion

As part of their end-of-semester course evaluations, students in every course respond to the following survey item: Based on my experience, this course helped me think creatively about the subject. The survey uses a 5-point Likert scale, ranging from 1=strongly disagree to 5=strongly agree. Student participation in the end-of-semester surveys is voluntary, and the survey data and statistical analyses are reported to instructors only after final grades are submitted.

Student responses to the "helped me think creatively…" survey item are summarized in Figure 1. The Figure 1 data show percentages based on cumulative responses from students in four different sections of the introductory materials taught by the same instructor over a period of four years (Fall 2004, Spring 2005, Fall 2005, Spring 2008). Also included in Figure 1 are summary data for student responses to the same survey item in *all* of the college's courses in the same semesters.

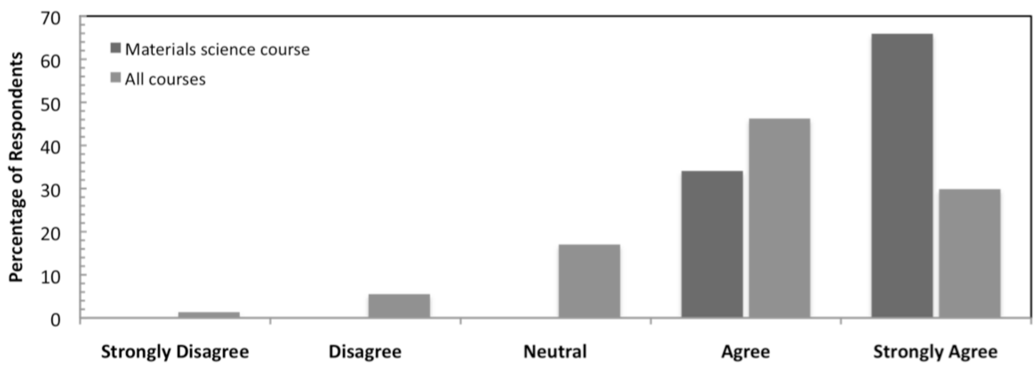

Figure 1. Student responses to the survey item: Based on my experience, this course helped me think creatively about the subject. Percentages are based on cumulative data collected over four semesters in the introductory materials science course (N=52). Summary data for all courses (N=2467) are shown for comparison.

The results clearly show that students perceive the introductory materials science course to be helpful to their creative thinking about the subject. Student responses are overall positive, both in the materials science course and across all courses at the college. This result is not surprising, as the engineering college emphasizes engaging pedagogies, and a high percentage of instructors at the college make use of active learning, collaborative learning, project-based learning, studio design learning, etc., in their classrooms. Statistical analyses do indicate, however, that the student responses in the materials course are significantly higher than the average responses across all courses. Despite the fact that students in the introductory materials science course are not designing physical objects or engaged in activities that are explicitly described as "design", they appear to be finding outlets for creative thinking.

The survey results show that students perceive the materials science course as an aid to their creative thinking, but the quantitative data do not indicate why this is the case. To elucidate the reasoning behind the student perceptions regarding creativity, individuals in the Spring 2008 section of the materials course were asked two follow-up questions:

1. What aspects of the materials science course helped you think creatively about the subject?
2. What, if any, aspects of the materials science course served as impediments to your creative processes?

Students had much to say about the contribution of the course format to their creative thinking. The following comments illustrate some of the factors they identified as important.

> I thought [the] self-directed nature of the projects helped me think creatively because we had to make our own decisions about what direction our projects should go. Since we had limited time, we had to choose what paths to pursue and what paths to not pursue. I also thought using the textbook as background knowledge but not the central focus of the class was effective.

> It was fun to mess around with different set-ups to see what sort of data we could get. Also, just in terms of making posters, we had to come up with a creative way to display all the work we had done in a compelling way, which was a different sort of challenge.

> The aspect that helped me think most creatively about MatSci was the freedom in defining our projects and determining what was relevant and appropriate for the problem we wanted to examine. Since each group had different projects, the "isolation" forced us to think independently…it was also up to us to further research topics within detail and to use that information in a creative way to answer the question we were pursuing in our projects.

> I feel that ability to think creatively about materials science was a direct result of the structure and design of the course. While the textbooks covered fundamental theoretical principles, they certainly didn't tell you how to analyze the artifacts… I also feel that the opportunity to craft the second and third projects to our interests helped us to think creatively, and also get more out of the class than if we had all been told to study steel.

> Being able to push boundaries and run extra experiments helped me to creatively think about the subject. The creativity for me came in when the expected result didn't match the actual result, and our team had to come up with another way to test the material in order to figure out what was happening.

> The class enabled students to study aspects of material science that were more open-ended (i.e. we chose our own project presentations, picked our own toys to study, and formulated our own testing schedule). I didn't feel as if my professor was dictating the learning process, making the learning process more of my own.

Students pointed to a variety of course design features as helpful to creative thinking. They note the importance of autonomy in their selection of topics or research questions, identification of relevant resources, design of analytical experiments, and setting of project directions. Students describe the course structure as one that provided for freedom, choice, and ownership, and they note the absence of instructor constraints in the project topics and experimental approaches. Some students highlighted the importance of play, e.g., "it was fun to mess around with different set-ups". In a departure from the more typical responses, one student commented on the role of the course examinations in his creative thinking:

> I can definitely say that one of the most effective aspects of the course, that actually also helped me think very creatively about the subject, was style of exams that you set. I found it great to be tested not only on the **understanding** of the material but also one's ability to apply it to a number of different, relevant and modern contexts. I reemphasize the word understand, as the exams did not necessarily test our ability to memorize the material, which in many cases, does not lead to

effective understanding. I think the approach was very conducive to the changes in the way we acquire knowledge nowadays, allowing us to call upon a number of different resources to obtain information about a subject and flavor it with contextual application.

This student viewed the open-ended, project-centered exam format as relevant to modern learning contexts and consistent with knowledge acquisition approaches used by today's students. A simple change in exam style from one that emphasizes a "right answer" to one that encourages individualized research and approaches provided a means for the student to internalize the learning and engage in creative thinking.

Students' comments regarding the influence of personalization, freedom, and choice on their creative thinking are well supported by the educational literature. Case study reports from several engineering educational contexts indicate that reduction in some of the typical constraints in engineering course experiences is necessary to foster student creativity,[27,28] and this finding is mirrored in the organizational management literature.[18] In addition to a loosening of constraints, creativity supportive environments must provide opportunities for problem discovery, experimentation with ideas, and exploration of alternatives – essential elements of the introductory materials science course described here.[8,28] Along with the freedom to *select* problems of interest, students must also be given a reasonable amount of authority or discretion to *solve* problems using their own strategies, without excessive controls imposed by instructors.

Student responses to the question of what aspects of the course impede their creative processes suggest that autonomy alone is not sufficient for creativity. The following student quotations reflect the complex nature of creative development.

While I cannot think of any specific impediments to creativity, I think the plans of inquiry for self-guided projects could have been better designed if we had a little more information going into each section. For example, I think my group would have tried to sinter the [metal] at different temperatures, so we could observe more distinct microstructures. While these oversights may have led to less thorough/insightful projects, I don't think they necessarily diminished the overall learning experience.

In most regards, the materials science course described here would be considered a success. If there was an area of negative feedback, it was the lack of structure in the form of lectures, exams, and homework problems.

Impediments to the creative processes - probably the largest was not being required to learn all the background ¨tools¨ of the trade -- if I learned enough to make a successful application in a project, that was all that I needed for both a good time and a good grade. I think I might have learned more if there had been more course requirements on ¨learning the toolkit¨.

Lack of resources in that our team did not anticipate the correct amount of materials we would need.

Although broken machines did push us to think creatively about how we were going to investigate our materials, they also served as huge obstacles.

I think it's a little limited just by the nature of being an intro class. A lot of times it's more fun to be creative about a subject when you know more about it. It can sometimes feel a little overwhelming to be creative and try to figure out what exactly is going on at the same time.

Students commented that a lack of background materials science knowledge and tools had a limiting effect on their ability to creatively design their projects. This response is expected, particularly early in the learning process, as creative production depends to some extent on domain-relevant knowledge and skills.[8] For example, if a Project 1 team is attempting to generate ideas for testing and analysis of the thermal properties of a coffee carafe, but they have not yet learned to use thermal analysis equipment or completed readings on thermal properties of materials, it is likely that their conceptual exploration and identification of alternative project approaches will be limited. This underscores the importance of the instructor's role as creativity facilitator in open classroom environments. Instructors must be able to intervene and interact with student teams in a manner that opens new pathways and inspires idea generation. In effect, instructors need to master the skill of providing just enough guidance for students to gain traction and continue their creative exploration.

A few students point to the lack of traditional structure as an aspect of the course that inhibits creativity. This comment usually refers to the lack of common knowledge acquisition by *all* students, since the course emphasizes an understanding of fundamental concepts explored through the variety of project topics. Without a checklist of knowledge gained, some individuals feel uncertain about the extent of their learning. Instructors should recognize that some students do not expect or desire high levels of autonomy in college classrooms. The transformation from teacher-controlled learning to self-directed learning can take significant time and create anxiety, and instructors must provide support, feedback, and encouragement to students who may not initially seek freedom in the classroom.

Students also noted that a lack of physical resources, such as broken equipment or insufficient materials, served to hinder their creativity. Resources (material, human, information, physical, etc.) appropriate to the creative task must be available, and instructors must be cognizant of the effect of resource provisions and constraints on creative processes.[18]

There are a number of additional considerations related to instructor facilitation and classroom climate that did not directly appear in the students' written responses. Risk-taking must be supported, and the failures that often accompany risky endeavors must be allowed.[18,28,29] Instructors must provide sufficient time for the incubation of creative thoughts, implementation of creative approaches, and "playing" in the classroom.[29,30] Finally, the pressure on students to perform must be minimized, or at least optimized. Pressure in the form of challenge that is internalized by students can provide for increases in creative output, but excessive time, workload, or grading pressures can stifle creativity.[9,18]

The responses in the introductory materials science course show that students perceive the learning environment to be conducive to their creative processes. But are the students generating creative outcomes? In the opinion of the instructor, the answer is yes. Without additional external evaluation, however, all that may be safely reported is that students are engaging in various steps of the creative process (e.g., identifying problems and goal, generating ideas, exploring alternative pathways, risk-taking, activating knowledge and skills, producing unique outcomes, etc.); students are exploring materials science topics in a self-directed manner; and students are developing high levels of motivation and self-efficacy. These positive indicators are promising, but further investigation of the autonomy-creativity connection among students in the materials science course is necessary.

Implications for Engineering Curriculum Design

The introduction to this paper described a pressing need in engineering education for courses that more effectively promote creativity. Educational literature and data from the introductory materials science course described above support the notion that the social-environmental classroom context influences students' creative thinking and creative skill development. In this section, curriculum design approaches that enable student autonomy and creativity are presented, and some of the challenges associated with autonomy-supportive classroom are discussed.

Challenges in Promoting Autonomy and Creativity

Students may be provided with a wide range of different freedoms and discretionary power over their learning, and educational research suggests that this control can lead to increased motivation, engagement, and creative skill development. The transition from traditional to autonomy-supportive classroom approaches, however, is not easy for students or instructors. Many challenges arise when engineering instructors begin to consider autonomy- and creativity-supportive settings. Removal of the many constraints typically placed on learning goals, tasks, resources, and environment provides for an entirely new environment that forces students and instructors to operate in unfamiliar roles. Instructors must recognize that learning to facilitate students' autonomous learning and creative development takes substantial time and effort. The modification of classroom environments may create situations of anxiety, doubt, cognitive and emotional tension, and feelings of incompetence. When faced with the significant challenges of educational change, the temptation is for instructors to reduce uncertainty through prescription of learning processes or strategies – to effectively constrain the exploratory space. Instructors are encouraged to embrace the ambiguity of new learning environments, and to avoid imposing their personal needs for control on students. With this in mind, instructors may expect to observe or experience the following challenges in autonomy- and creativity-supportive environments:[31]

1. Student uncertainty. High levels of learning autonomy may bring about anxiety, cognitive dissonance, and a challenge level that is too high for the achievement of "flow", particularly in the more control-oriented students. Self-directed learning environments that promote creative approaches do not provide a clear "best way" or "right answer", and the room for error, or even failure, may be difficult for some students to manage.
2. Instability. The autonomous, creative environment is dynamic and continually changing, providing for a lack of predictability in student and instructor responses.
3. Need for Responsiveness. Instructors will be asked to respond, even when they do not know how to respond. Honesty and open discourse are highly effective in these situations.
4. Lack of control. Autonomy brings with it the potential for student paths that are incongruent or in tension with the stated learning objectives. Open communication may aid alignment of instructor and student interests and goals.

5. Evaluation. How does one grade a set of projects or problems that are all different? Assessment rubrics based on broad competencies and higher-level skills are useful in these situations.
6. Creative personality traits. Some students are more willing or more able than others to engage, and some students hesitate to share their ideas for fear of criticism. Instructors can devise creativity exercises that help to incorporate ideas from all students.
7. Creative Differences. Diversity of opinion is good, right? Emergence of creativity among team members will result in conflicts of opinion that must be negotiated and resolved to ensure team coherence and progress. When working on teams, students need tools or techniques that enable them to converge their creative responses into a common vision.
8. Flattening of the power structure. Flexible, open, collaborative learning environments demand non-traditional interactions between instructors and students. Learning to effectively relate to students in an open environment requires skill development and significant time and effort on the part of instructors.
9. Physical space. Many classrooms have a traditional floor plan (student seats facing the instructor at the front of the room, or fixed benches or desks), and these physical constraints can pose particularly difficult challenges. Be creative.

If creativity is to emerge, and intrinsic motivation is to rise, students must feel a sense of freedom and control in their learning. As such, the personal, social, or classroom environmental issues that threaten to inhibit creativity must be resolved. These difficulties in resolving course-specific issues are often exacerbated by institutional-, college-, and program-level factors. Instructors may face significant challenges related to institutional culture and norms, scheduling constraints, resource limitations, and established expectations for curricula. For example, most engineering students and instructors currently operate within programs designed with traditional lecture-lab courses in mind. In these cases, academic schedules, faculty teaching loads, and course budgets are all built around the lecture-lab model, and modifications aimed at enhancing autonomy and creativity may have far-reaching effects that disrupt the equilibria within the degree program and beyond.

Guidelines for Promoting Autonomy and Creativity

The following guidelines integrate the present discussion with recommendations from several literature sources that describe features of creativity-supportive classroom climates. Engineering instructors may consider this list in the design and development of new assignments, courses, and curricula:

1. Introduce tasks or projects that are heuristic rather than algorithmic. Heuristic tasks are defined as those without a clear and readily identifiable path; algorithmic tasks have a clear, straightforward solution.[8]
2. Provide divergent thinking tools and activities (e.g., idea generation techniques). Creativity-relevant skills can aid student exploration.[8,20,28]
3. Adopt active, engaging pedagogical approaches, such as project-based learning, studio design learning, problem-based learning, etc.[32]

4. Create a flexible and supportive power-authority-influence structure in the classroom. Avoid controlling tactics and excessive use of pressures and extrinsic rewards and punishments.[5,13,31]
5. Allocate sufficient physical and information resources for creative exploration.[18] Be careful not to over specify the human resources needed for a task.[31]
6. Provide high levels of freedom and autonomy, as these will lead to individual ownership, control, and internalization of learning and creative processes.[13,18]
7. Encourage and recognize risk-taking and innovative approaches, regardless of whether they are successful or unsuccessful.[17]
8. Adopt humanistic attitudes. Empathize with students. Express support, openness to ideas, belief in student capabilities, and shared commitment to the learning process.[18,32,31]
9. Allocate plenty of time for play, incubation of creative thoughts, and implementation of creative approaches.[29,33]
10. Encourage open discourse. Provide significant, constructive feedback.[32]

Obviously, these recommendations extend well beyond changes in course content. As with any significant reform effort in education, the modification of curricula to include autonomy- and creativity-promoting activities requires changes in the social, environmental, and affective aspects of the learning approaches. Significant transformation takes time and enormous effort, but even small steps in the direction of increased autonomy and creativity may bring about positive outcomes in student learning.

Summary

Jean Piaget is quoted as saying that, "The principle goal of education in the schools should be creating men and women who are capable of doing new things, not simply repeating what other generations have done; men and women who are creative, inventive and discoverers, who can be critical and verify, and not accept, everything they are offered."[34] The engineering educational community affirms that autonomy and creativity are critical capacities for the success of our graduates in today's rapidly changing global environment. Research shows that autonomy – freedom, choice, control, ownership – is necessary for creative skill development, and the positive correlation between autonomy and creativity in individuals suggests that synergistic advancement of these may be possible in undergraduate classrooms. The design and implementation of engineering curricula conducive to autonomy and creativity is not easy, however, and there is a significant need of more formal evaluations of the interactions and correlations among various creativity determinants in different undergraduate engineering classrooms.

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