2006-1851: HOW MUCH CAN (OR SHOULD) WE PUSH SELF-DIRECTION IN INTRODUCTORY MATERIALS SCIENCE?

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Abstract

A capacity for self-directed, life-long learning is often cited as a critical skill for tomorrow's engineers. The student response to high levels of self-directed learning, however, is not always positive, particularly in introductory level courses. Some students enthusiastically embrace the control over their learning in open-ended situations. Other students, however, become frustrated and disheartened, and ask to be returned to a comfortable state of structure, guidance, and traditional learning. The self-directed knowledge acquisition in technical disciplines has historically been a controversial approach that deserves our close examination, as some students cite self-direction as a positive contributor to learning, while others report decreases in learning due to student control. In this paper, we explore the issues surrounding student directed learning in a project-based introductory materials science course. We present preliminary data on the student responses to open-ended projects and self-guided learning, with particular emphasis on the development of and changes in attitudes and self-perceptions of learning throughout the semester. Possible causes of student responses to self-directed learning are considered, and particular attention is focused on student comfort in self-directed environments and its relation to learning processes.

Introduction

The reality is that someday our undergraduate students will not have us by their sides. Soon we will not be there to guide their learning, to structure their assignments, to inform them of the important bits of information, or to provide feedback on their work. As learning facilitators, we hope that long before that day arrives, our students will learn a few important lessons about learning. Undergraduates should recognize that they have the capacity to acquire and construct knowledge, to set goals and direct their learning process, and to assess and reflect upon their learning strategies and actions.

Calls for educational reform emphasize the need for new learning approaches that are student-centered and that aid development of broader skills and attitudes to complement traditional knowledge acquisition.[1,2] A capacity for self-direction and life-long learning is often identified as a critical outcome for educational systems, and many assert that instruction that is focused on self-directed learning best facilitates understanding.[3] We are clearly asked by the Accreditation Board for Engineering and Technology (ABET) and other organizations to promote the development of students' life-long learning skills through our curricula.[4,5] Engineering educators generally agree that these skills are important – even essential – for success in today's technology-centered environments with their ever expanding information bases. But how do we best promote student self-direction? One solution may be for educators to develop (i) a familiarity with the purpose and value of self-directed learning, (ii) skills in implementing and facilitating *pedagogical approaches* that effectively engage students in self-direction, (iii) a sensitivity to and understanding of the *student behaviors* in self-directed learning environments, and (iv) an ability to modify our curricula in a manner that responds to student needs and promotes student awareness of the learning process.

How do we best engage students in self-directed learning activities? The answer may lie in the design of active, student-centered learning environments (e.g., problem- and project-based learning) that emphasize inquiry, problem-solving, and student control over the learning process. Although project-based learning and problem-based learning approaches have been used for many years in diverse ways and across many disciplines, much attention in recent years has focused on the use of these pedagogies in engineering education. These two forms of active learning are quite similar and share the same emphasis on student learning rather than instructor teaching.[6,7,8,9,10] Student self-direction is generally considered an integral component of problem- and project-based learning approaches. Evaluations of problem- and project-based learning approaches have shown increases in motivation and satisfaction, problem-solving ability, communication and teaming skills, occupational preparedness, knowledge retention, and capacity for self-directed learning.[7,9,11,12,13,14] Research has also shown that these approaches can lead to improvements in content acquisition and performance on traditional exams, although some of these effects are still far from generally accepted, particularly in the engineering community.[12,13,14,15,16]

Despite the general agreement that self-directed learning provides learning benefits, and the push toward pedagogical approaches and curricula that incorporate exercises in independent learning, issues remain. Questions regarding appropriate degree of self-direction in curricula or level of student control over knowledge acquisition remain debatable, particularly in engineering education. The self-direction discussion remains heated because the content acquisition questions, which many educators view as vitally important in undergraduate engineering education, remain only partially resolved. Recent meta-analyses comparing students in problem-based and traditional lecture courses indicate that students in self-directed environments generally perform at an equal or higher level on knowledge acquisition examinations.[13,16] Despite these findings, many engineering faculty are quick to identify losses in content acquisition as a significant downfall of student-directed approaches.[9,14,17,18] Some researchers have suggested that the knowledge acquisition requirements of science and engineering are different from those in other disciplines, and that the hierarchical knowledge structures of topics such as mathematics and physics require that content not be overlooked or covered out of order.[17] Perrenet et al. state that problem-based learning “may not always lead to constructing the ‘right’ knowledge,” and some reports suggest that that faculty direction of content through lectures is required to ensure complete coverage of subjects and proper development of students’ metacognitive skills.[19,20] Many believe that significant faculty guidance through lectures is necessary to drive effective student decision making.

Student attitudes pose an additional barrier to high levels of self-direction. Many students, when placed in control of content acquisition, cite high frustration levels, a lower perception of acquired knowledge, and concerns that they are not learning the “right stuff.”[14,21,22] The student discomfort is understandable. In transitioning from a traditional learning mode to a self-directed mode, students need to embrace unfamiliar roles, responsibilities, and behaviors. Although frustration and dissatisfaction tend to decrease with time,[14] these responses are not easy to understand and overcome, and they may have significant effects on student-faculty interactions, classroom dynamics, and course evaluations. A discussion of some sources of student frustration is provided in the Student Responses section.

Another important impediment to student self-direction that is sometimes overlooked is the faculty resistance to handing control of the learning process to students. Actually, “resistance” may be too strong a word to describe the faculty response to student-directed learning approaches. The faculty response may be more based on a different conception of student learning than an overt resistance to student-centered approaches.[23]

The level of student self-direction, especially of knowledge acquisition, is an important variable to consider in designing learning experiences and assessments. The level of self-direction that is set in a particular curricular environment, and the instructor facilitation of the learning process, may have dramatic effects on student responses and on student engagement in the learning process. Understanding student behaviors in self-directed learning environments is critical to our continued development of curricular strategies that address student needs and promote students' self-directed learning. In the following section, we describe our project-based approach to introductory materials science, with particular attention on aspects of the course that we believe promote the development of students' self-directed learning skills.

Course Design and Goals

Olin's introductory materials science is a project-based course that combines new pedagogical practices with modern laboratory facilities. The introductory materials science course employs a project-based approach and emphasizes hands-on experimentation. The course's strong linkages to everyday stuff – products such as sporting goods, tools, and toys – as well as cutting edge materials and processes are highly appealing to Olin's undergraduate engineering students.

The course is designed to provide significant opportunities for student self-direction. Several key elements of the course give students practice in controlling their own learning process. The course features open-ended projects with self-designed experiments, self-guided knowledge acquisition and synthesis, self- and peer-assessments, and self-reflection essays. The pertinent course elements are briefly described below, and additional details on the course design and implementation may be found in the literature.[22,24]

The course is organized around three open-ended projects with specific goals and constraints (Table I). The team-based projects serve as the primary pedagogical mechanism in the course, encouraging students to develop experiential understanding of content and methods. The projects provide motivating context and allow students to directly apply fundamental theory, shape project goals, and practice analytical processes. The degree of instructor-defined constraint on the projects decreases as the semester progresses. This important feature enables students to build increasingly sophisticated life-long learning skills throughout the semester by gaining increased control over their learning strategies and educational process.

Each project has accompanying constraints, deliverables, and assessments. Although the broad learning objectives are the same for everyone, each student team studies a different topic or material system. For example, to attain the Project 1 goal of connecting composition and

Table I. Materials science course projects and learning objectives.

Theme and Allotted Time	Goals and Objectives	Constraints
1. Materials Analysis of a Common Object 5 weeks	• Develop basic laboratory and experimental design skills • Collect and analyze data on material composition, structure, and properties • Explain connections among material properties, chemical composition, and atomic structure and bonding • Identify characteristics of materials that make them suitable for use in common products • Develop graphical and visual communication skills	Laboratory experiments limited to property testing and structural and compositional analyses of a common product (e.g., tools, toys, sporting goods).
2. Microstructure-Processing-Property Connections 5 weeks	• Design and implement experiments to investigate a question related to microstructure-processing-property relationships in a material system • Collect and evaluate experimental data on material microstructure, properties, and processing, and compare with predictions about how property changes are expected to occur as a result of processing • Examine the relevant context of an alloy system, and research modern alloys and processing techniques • Develop oral, written, and graphical communication skills	Materials and processing limited to alloys that are of technological importance. Projects must include some processing and microstructural analyses.
3. Modern Materials and Methods 3 weeks	• Design and implement an experimental procedure for analysis of a modern material, component, or process • Identify appropriate information resources for the project investigation • Articulate structure-processing-service environment-property relationships in modern materials systems • Evaluate materials selected for particular technical applications, and recognize relationships between materials selection and design • Examine the relevant context of a modern materials technology • Develop communication skills in presenting results	Projects limited only by time, course budget, and laboratory resources. Limited project time tests students' ability to find relevant sources.

structure to properties, one team of students may spend the majority of their time analyzing polymeric structures and properties in skateboard wheels, while another team may explore the effects of testing temperature on the mechanical properties of various alloys used in a padlock. Similarly, in Project 2, one team may examine the effects of welding and heat treating on aluminum alloy microstructure and properties, while another team may explore the effects of cooling rate on the microstructure and properties of cast manganese bronze.

A high level of self-direction of content acquisition and synthesis ideally enables students to master the course objectives while becoming more aware of their own learning styles. Projects run concurrently with a stream of textbook readings and homework problems to address concepts that are relevant to the project. In Project 3, where the level of self-direction is highest, homework problems and readings are not assigned by the instructor. Rather, student teams are responsible for the identification and acquisition of pertinent information resources (web, library, textbooks, etc.). But identification and acquisition of information is not sufficient. To attain success in the course, students must learn to synthesize information into a coherent understanding so that they may *apply* the knowledge in their project and *explain* the significance of the knowledge to their classmates.

Although students acquire some fundamental materials science knowledge through homework assignments and connection of project topics to theory, the project approach shifts the course focus from a predetermined and well-defined set of content to broader outcomes and higher level skills. In completing self-directed projects, the student teams cover different content, focus on different aspects of the project-based learning process, and acquire depth of knowledge in different areas. Students are more likely to pursue topics and skills if they are relevant to their project goals.

The open-ended projects and emphasis on student self-direction make assessment in the course rather challenging. The learning environment necessitates assessment methods that are designed to gauge broad competency development in addition to traditional knowledge acquisition. To address the differences in specific content learning, fundamental (and powerful) concepts and broad learning objectives are emphasized throughout the semester. Olin College's provisional competency assessment system is used for evaluation of student learning, enabling measurement of student knowledge and skills according to expected levels of achievement in areas such as qualitative analysis, quantitative analysis, diagnosis, teamwork, communication, and life-long learning.[25]

All course assessment mechanisms are based on the competency assessment system and designed with project open-endedness in mind. Each course assignment comes with a description of which competencies will be assessed and how they will be assessed, and detailed grading rubrics are provided with the major project assignments. Team projects are assessed according to students' abilities and skills in communication (oral, written, graphical, and visual), quantitative analysis, qualitative analysis, and diagnosis. For each major project assignment, the instructor provides students with detailed written feedback and a letter grade in each competency area.

Written exams are administered at the end of Projects 1 and 2. These individual exams naturally merge content acquisition objectives with skill building objectives. Open-ended exam questions test qualitative analysis, quantitative analysis, and diagnosis abilities through questions focused on the analysis of experimental data, prediction of the effects of materials processes, and design of experiments to determine the feasibility of engineering tasks. To attain success on the individual examinations, students must demonstrate that they can synthesize fundamental content knowledge and critical thinking skills, and apply these to unfamiliar situations based on real-world problems.

Peer-assessment, self-assessment, and self-reflection on learning processes are emphasized throughout the semester. Teaming skills are assessed through peer- and self-evaluations at the end of each project. In the teaming evaluations, students provide a numerical rating for themselves and their teammates, and they write self-reflective comments on teaming-related lessons learned during their project experience. The instructor collects the teaming evaluations and provides summary comments to individual students. A self-assessment of life-long learning skill development is included as the final piece in the course assessment picture. For this assignment, students are asked to write a self-reflective statement that describes how the course experiences contributed to development of their life-long learning skills and an understanding of their learning process.

Formative assessment is an important aspect of competency development in the materials science course. A continuous stream of informal competency feedback is provided to students during the projects through conversations and discussions between instructors and project teams. After submitting project reports or posters and receiving instructor feedback and suggestions, students can edit their deliverables based on the feedback and re-submit their work. Homework problems, although assigned regularly with posted due dates, are self-assessed rather than being collected and graded by the instructor. The instructor posts the homework assignments and solutions on the course web site on a weekly basis. The lack of formal submission deadlines and emphasis on self-evaluation place more of the responsibility for learning on the students and provide practice in important aspects of life-long learning.

Student Support and Teacher Role in the Self-Directed Learning Environment

Are students really expected to both experience a previously unknown field and simultaneously determine which aspects of it warrant the most attention? For success in self-directed learning, students must be able to note which experiences lead to a more comprehensive understanding of a subject, and which experiences are simply anomalous occurrences with little applicability to broader contexts. How are students to make sense of their observations?

To describe the introductory materials science as a pure self-directed learning experience is not entirely accurate. The course certainly offers an introduction to and promotion of self-directed learning, but it does not toss students into the deep end of the pool with no hope but to drown. As indicated in the previous section, students are provided with an intentionally designed support environment to aid learning. Such support systems are often found to be necessary to ease the student transition into self-directed learning. The materials science course included several key components: social and collaborative learning environment, faculty facilitators, and assignments with more traditional structure. Relevant background and application of these support components is described below.

Social Environment

It has long been known that social environment can play a vital role in learning. Social constructivist views of learning emphasize the importance of social context, social process, and social interactions in learning. Peer discourse and feedback, activities that are dictated at least to some extent by the pedagogical approaches and classroom environment, are essential for effective construction of knowledge and individual understanding.[26] The effectiveness of collaborative learning seems inextricably linked to each team member's ability to communicate and conduct himself or herself effectively within the group. Peer interaction is becoming more emphasized in both the workplace and in the classroom, and some believe that a person's capacity to network has become more important to success than one's intelligence quotient. Faculty-student interaction and student-student interaction have been identified as the two most influential factors leading to a general positive educational outcome.[27]

Although a student's attitude and comfort in a team or classroom has long been known to directly correlate to his or her success, traditional teaching methods are usually not aimed at addressing group contexts. Teams of people who get along well and respect each other are naturally more conducive to high quality work, and small student group learning has exhibited advancements in students' ability to manage or overcome the inherent awkwardness and incompatibilities associated with team formation.[28] Students who learn in a collaborative team environment also showed an increase in perceived social support from both teachers and from other students. This improved social comfort aids group effectiveness, but also increases student integration, provides social incentives for attendance, improves self-esteem, and adds to students' sense of belonging.[28]

All project work in the materials science course is collaborative. From the first day of class, teams work together to set goals, plan experiments, acquire and interpret information, and develop skills and understandings. In addition, the instructor encourages collaboration on all homework assignments. The emphasis on *team* engagement with problems creates a community learning environment in the materials laboratory, and an awareness of team support appears to decrease the students' cognitive load.

Teacher's Approaches and Attitudes

The second essential characteristic of the support system is acceptance of a non-traditional role by the instructor. The role of the person traditionally called a teacher or instructor is quite different in student centered learning. To facilitate students' journey and their process of sorting and interpreting information into some meaningful structure of understanding, instructors must embrace the guiding, facilitating, and enabling role of the tutor.[4]

Because self-directed learning emphasizes the personal meaning and negotiation of experiences, learning facilitators must operate on a different level with the students than traditional teachers do. To be an effective tutor, a teacher must not only have the large knowledge base traditionally required of him, he must also develop several areas of classroom demeanor.[14] A tutor must possess "the ability to express oneself in the language of the students, using the concepts they use and explaining things in ways easily grasped by students."[29] Tutors must also serve as a role model for students, showing them that it is possible to meaningfully negotiate open ended problems and exhibiting the skills needed to do it. Students observing an expert's behavior in a shared environment have a much richer context and background to the decisions the expert makes, and students can more quickly apply the expert's knowledge is subsequent contexts.[30] Finally, facilitators must be able to promote a group's awareness of its own processes, stimulate feedback within a group, guiding groups toward appropriate learning areas, and guiding the integration of group experiences into knowledge.[31]

Although the initial switch to non-traditional, student-centered learning approaches in the materials science course was initially awkward for the instructor, several semesters of experience has quelled the discomfort and eased the apprehension. The instructor now avoids the "content expert" position and embraces a non-traditional role as facilitator of the learning process. Rather than delivering fundamental content through "efficient" lectures, the materials science instructor asks thought-provoking questions during collaborative project work periods. Formative assessment is an important aspect of the instructor's promotion of student development in the course. A continuous stream of informal feedback is provided to students during the projects through conversations and discussions between instructors and project teams. Instructor assistance is always available, but the "answers" are not provided up front in a nice, neat package. Individuals and small project teams are encouraged to develop a clear understanding of their project goals and an awareness of the learning processes they may exercise to attain the goals.

An additional boon to course delivery and student learning comes via student laboratory assistants. Experience has taught us that undergraduate students who are properly trained and experienced in self-directed learning approaches can assume the tutor role in much the same manner as the faculty facilitator. The student assistants offer an additional benefit: they have been through the course and can tell younger students that everything will be okay. This first-hand experience by the tutors enhances the social environment by easing the younger students' uncertainty and discomfort, by providing an added spark to students' creative thinking, and by aiding students' engagement with the project and problems.

Traditional Sources of Structure

Traditional sources of structure in the materials course include scheduled class time and a set of course-related information, assignments, and materials that are designed to smooth the transition to self-directed learning and gently nudge students in the direction of the learning objectives. In the first two projects, the instructor provides learning footholds in the form of regularly assigned homework problems and readings that are designed to build competence in the fundamental bits of materials knowledge and increase student confidence in the topic. The homework sets include both simple textbook problems and open-ended challenges that require higher-level thinking and synthesis of multiple concepts. The open-ended homework problems are intentionally designed to help prepare students for the open-ended projects. Due dates for all materials science readings and homework are specified, but none of the completed homework is collected. Instead, homework solutions are posted at the due date, and students are strongly encouraged to assess their own work and seek assistance when necessary.

The self-directed learning purists may view this provision of traditional structure as a copout – a failure to fully commit to new learning approaches. But as noted earlier, students do not easily transition from traditional learning roles to new ones. Such support systems are often essential for successful implementation of flexible, student-directed learning experiences, particularly those that occur early in the curriculum.

Survey Questions and Goals

Students in one section of the project-based introductory materials science course were asked to respond to a simple survey several times throughout the semester. The primary purposes of the survey were to collect information on student attitudes toward the pedagogical approaches used in the course; to evaluate student self-perceptions of learning; to identify particular difficulties arising from the learning approaches; and, if possible, to identify differences in response by gender. The survey was not intended to provide a deep understanding of *why* students responded a particular way. Rather, it was designed to highlight issues for further investigation.

The survey was administered in Week 2, Week 7, and Week 15 of the semester-long introductory materials science course. The course section was nearly gender-balanced, with 10 men and 8 women. The response to the survey was high (72-94%), but the sample size for the survey is very small (N=18). Thus, the data and analyses presented here should be interpreted as a "work in progress" and a source of discussion, rather than as an extensive or long-term research investigation.

The complete survey was divided into three sections: I. Learning Approaches, II. Course Effectiveness, and III. Course Objectives. The Learning Approaches section included statements related to student self-perception of the learning environment and learning effectiveness, and student comfort levels with the learning environment. The Course Effectiveness and Course Objectives sections in the survey were identical to sections by the same name that are used in the end-of-semester course evaluation surveys in all courses at Olin College. Course Effectiveness generally focused on student interest and motivation levels, and Course Objectives was aimed at student perception of learning with respect to the course learning objectives.

Each section included a list of survey statements. Students were asked to express their level of agreement with each statement. A five point rating scale was used: (1) Strongly Disagree, (2) Disagree, (3) Neutral, (4) Agree, and (5) Strongly Agree. Students were also given the option of a Not Applicable response. In addition to the survey statements, space was provided for written comments. This paper presents the numerical student responses to select items from the Learning Approaches and Course Effectiveness sections of the survey. Student responses to the Course Objectives survey items are not presented or discussed here.

Student Responses

Perception of Learning Environment

The instructor describes the introductory materials science course to students as a "project-based, self-directed learning experience." The first two survey items were designed to determine if the students perceive the course in the same manner as the instructor. This may seem like a trivial exercise, but casual conversations with students regarding course experiences will elucidate the fact that student perceptions of activities often differ dramatically from faculty perceptions, descriptions, or intentions.

As shown in the survey responses (Figure 1), the students concur with the instructor's description of the learning environment. Student perceptions of the course experiences remained similar throughout the semester, despite the loosening of project constraints and increase in the degree of student self-direction as the semester progressed.

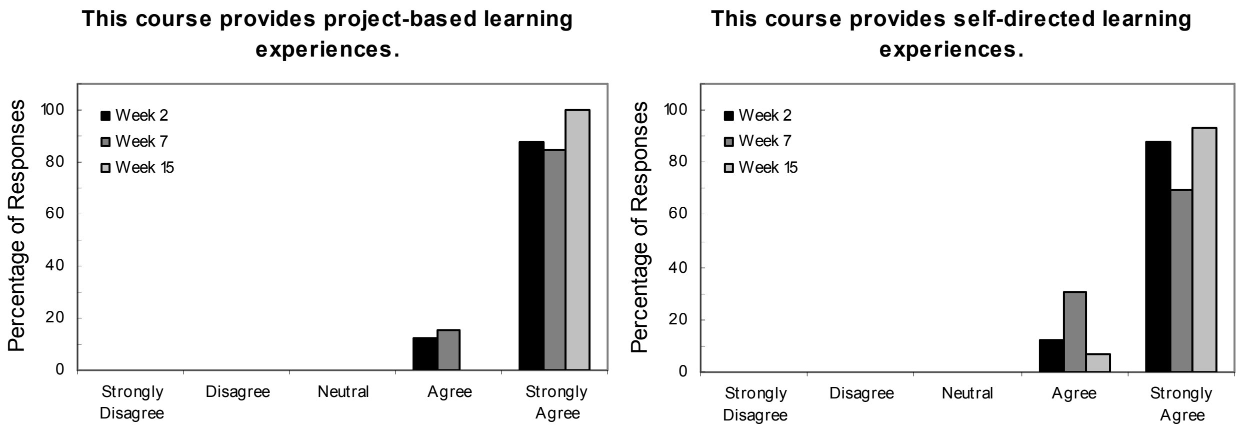

Figure 1. Student responses to survey questions regarding perception of learning experiences.

Motivation and Interest Levels

Maintaining student engagement is critical for achievement of learning outcomes. Motivation and interest levels are particularly important in environments that place enormous responsibility for learning on the students. Only through effective intellectual stimulation and strong engagement throughout the course will students actively pursue deep learning in an environment that does not provide the traditional structure to which they are accustomed.

As noted in the Introduction section, problem- and project-based learning environments that emphasize self-direction have traditionally shown benefits in student motivation levels. Interest levels tend to be high when students feel control over their learning,[32] when students consider the problems they study authentic and relevant to their personal needs, and when students are engaged in the hands-on use of tools and artifacts. The creation of a "classroom community" in collaborative, team-based settings is also believed to contribute to student motivation.

The survey responses indicate that the materials science course effectively stimulated student interest and helped students think creatively about the subject (Figure 2). Students expressed a relatively high level of interest in the materials science course throughout the semester. This response was not surprising, given the instructor's past experiences in the project-based course and the literature reports regarding student motivation in active learning environments. The course was intentionally designed to incorporate features that are known to promote creative thinking and engage students in the learning process. Students start hands-on projects on the first day of class, and their application of fundamental theory in the laboratory does not cease until the end of the semester.

Although the student responses to the motivation-related survey items were high throughout the semester, there is a noticeable trend toward more positive responses as a function of time. The precise cause of this effect is unknown, but it may result from several factors. First, as noted above, the level of student control of and choice in projects increased throughout the semester. For the final project (last 3 weeks of the semester), students initiated and designed experiments

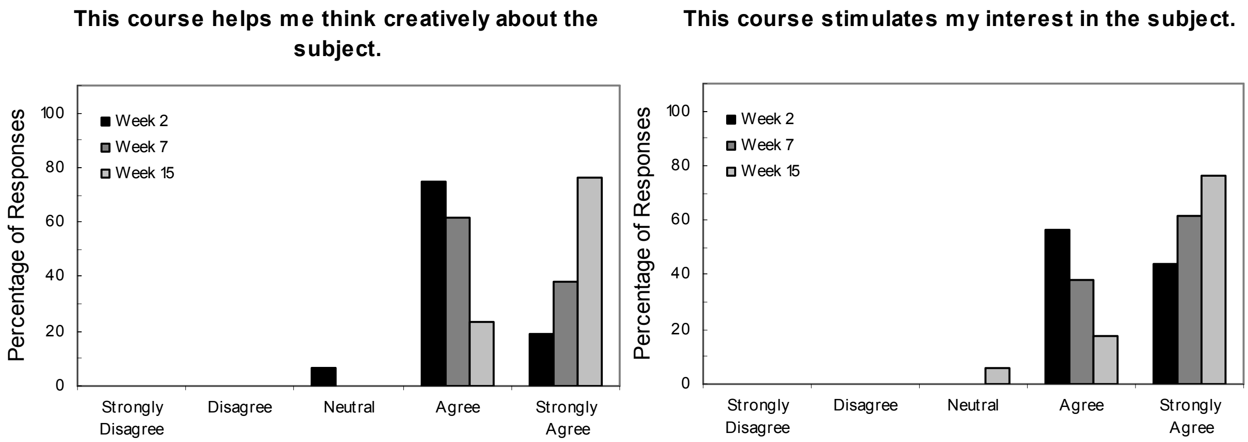

Figure 2. Student responses to survey questions regarding interest stimulation and creative thinking.

to investigate *any* modern material or process. This freedom to pursue project topics of individual or small team interest may be directly linked to the high student stimulation.

Second, the students were given control of their final project deliverables, and they were not assessed on a body of fundamental knowledge defined by the instructor. Students identified the content required for their project and controlled their knowledge acquisition. There was no instructor-designed examination to cover Project 3 concepts. The elimination of assigned homework and lack of a final exam may have served to lower the students' cognitive load by decreasing the risk of failure on teacher-defined tasks. When first attempting the "design your own" final project, the instructor was concerned that knowledge acquisition may be sacrificed during the final project phase. Anecdotal evidence indicates that this is not the case for most students. Many students actually exert more effort in the final three-week project than in the earlier projects. It could be that students are compelled by the opportunity to finally apply the knowledge and skills they have been synthesizing all semester to a topic of deep personal interest.

A third reason for the gradual rise in student interest may be an increase in student *comfort* with the pedagogical approaches. Student comfort in active learning environments is related to a number of factors, some of which are discussed in the following section.

Student Comfort in the Learning Environment

The literature consistently reports that students express some degree of discomfort when they are thrown into self-directed learning environments. As instructors, we expect to observe this discomfort and frustration, particularly near the start of the semester, when students must adjust to the new learning mode. Student discomfort is expected to decrease with time, and the initial period of frustration is typically followed by post-transition satisfaction.[13,14]

Figure 3 shows the materials science course survey results for survey items related to students' level of comfort with the pedagogical approaches. Given the literature reports, the survey data

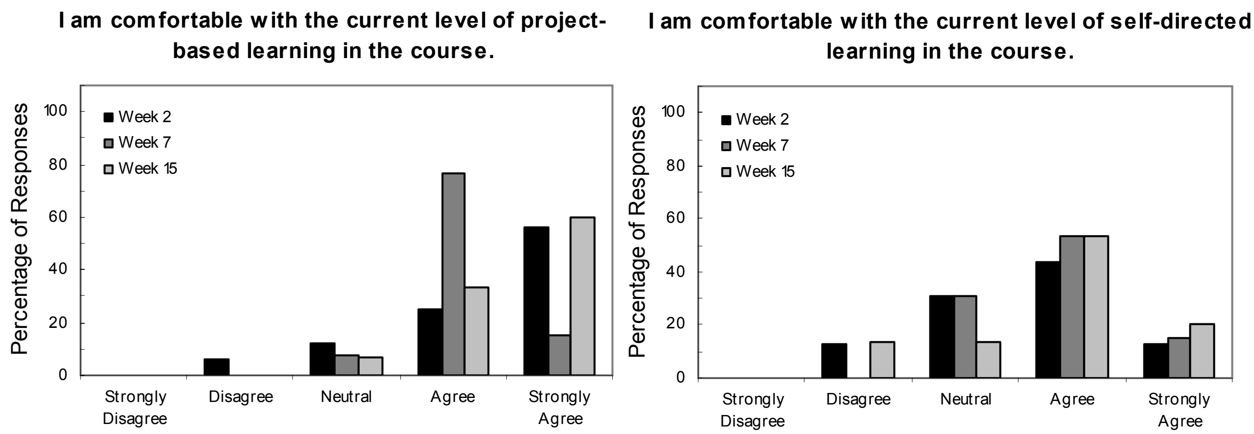

Figure 3. Student responses to survey questions regarding comfort levels with the pedagogical approaches.

regarding student comfort in the materials science course were somewhat surprising, and several issues related to the survey results merit further discussion.

One interesting outcome is the difference in student response to the questions regarding their comfort with project-based learning versus self-directed learning. The survey data show that students are generally more comfortable with the project-based aspect of the learning environment than with self-direction. It seems clear that students in the materials course regard the two pedagogical approaches as separate elements of the learning environment. This may have some interesting ramifications on our thinking about course and curriculum design, as some instructors may consider self-direction to simply be an inherent characteristic of other forms of active learning (e.g., project- or problem-based learning). These limited data indicate that perhaps we should think of self-direction as a separate knob that we may adjust in the design of learning experiences.

Another interesting outcome is that the materials science students' comfort levels with project-based and self-directed learning do not follow the anticipated "low to high" trend. Given the limited data and the design of the survey, the reasons for the unexpected trends are not entirely clear, but some possibilities are hypothesized and discussed below.

Comfort with Projects. Student comfort with project-based learning is relatively high in each set of survey responses, but the data follow a high-low-high trend. This trend may be related to the project activities that were underway during the weeks the survey was administered. In week 2, students were actively involved in implementing experiments for their first project (analysis of common products). They were gaining their first exposure to the materials lab – learning to use mechanical testers to break stuff, thermal analyzers to melt stuff, and spectrometers and diffractometers to identify stuff. Most students were likely devoting most of their energy to the project and putting off their reading and homework. The first exam was still a few weeks away, after all, so there was little need for concern. During week 7, students were in the beginning stages of their second project, researching pertinent materials theory, and planning and implementing experiments. By this time, they had completed several major assignments, and they had received instructor assessments on the Project 1 deliverables and the first examination. Many students were playing "catch-up" with the homework and readings they should have been doing on a more regular basis. At the time of the final survey (week 15), the course was essentially winding down. Most students felt some assurance that they would be able to complete the deliverables for the final project that they designed, and that they would survive the course. There may have been a sense of relief and satisfaction upon completion of the project-based course.

Comfort with Self-Direction. Student comfort with self-direction does not increase over time as the literature indicates it should. Comfort levels increase slightly between weeks 2 and 7, but remain nominally equal at weeks 7 and 15. It could be that one semester is too short a time scale to observe significant decreases in discomfort for this particular group of students. Measurements over longer times and across different courses might provide the expected trends. The relatively stable comfort levels may also be a direct result of the continually increasing level of self-direction throughout the semester. Recall that the final project was *entirely* self-designed and self-directed. In contrast, the first project included relatively well-defined constraints and was accompanied by instructor assigned homework and readings. Could the removal of structure and increased level of self-direction in the final project have prevented students from reaching a truly comfortable learning state? Obviously, a deeper understanding of the student responses is necessary to answer this question.

The *root causes* for individual student discomfort with the self-directed learning aspects of the introductory materials science course remain unclear. We do not fully understand *why* the discomfort occurs, *why* it is present to a greater or lesser degree in individuals, and *why* the feelings of frustration persist over a longer period in some individuals. Written student comments, instructor observations, and instructor-student interactions suggest multiple sources for discomfort, including low capacity for self-regulation, difficulty in knowledge construction, and difficulty in engaging in a social learning environment.

There is some evidence in the students' written comments that the discomfort stems from an inability to regulate their own learning process. For example, many students reported difficulties completing the reading assignments and homework problems by the posted due date, and they suggested that the instructor should *collect the homework even if the work is not assessed by the instructor.* As reported in the literature, the capacity for self-regulation and the learning of self-regulatory skills are important considerations in self-directed learning environments.[23] Students who have trouble planning their time, organizing their projects and experiments, and finishing their homework or readings on time will naturally feel some discomfort and dissatisfaction with self-directed learning.

There are also clues in the students' written comments and verbal feedback that indicate that some discomfort is due to difficulties in knowledge construction and utilization. Many students are able to collect bits of theoretical and experimental information, but are unable to effectively synthesize the knowledge into a coherent understanding. If students have difficulty grasping the powerful big picture, they are bound to feel some discomfort with the self-directed learning mode.

More evidence related to student comfort is found upon examination of students' social behavior. Some students seem to have trouble engaging in the social interaction and collaborative processes that are necessary for success in the project-based learning environment. Without connection with their peers and support from their team, students experience much more difficulty and discomfort in self-directed learning.

Relationship between Comfort and Structure. Figure 4 provides student reactions to the amount of structure and guidance in the materials course throughout the semester. The data follow a similar trend as observed in the "comfort with self-direction" survey item. The written student comments clearly indicate a desire for *more* guidance, not less. Discomfort due to self-regulation or knowledge construction problems is likely one cause of the frequent student pleas for additional structure (e.g., lectures). Other related factors may also contribute to the calls for instructor guidance. These factors include difficulty dealing with ambiguity, low confidence in problem solving, and low self-perception of aptitude.

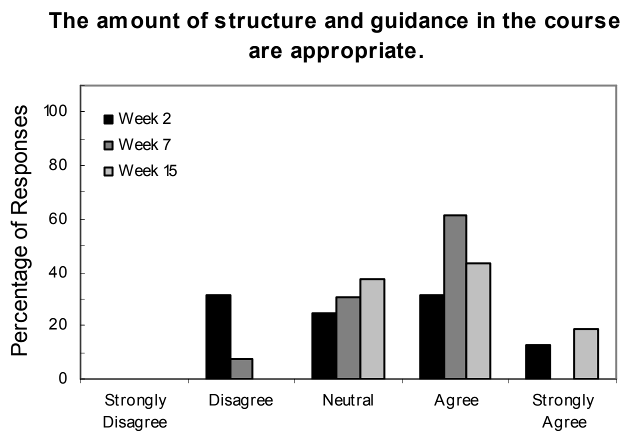

Figure 4. Student responses to a survey item regarding guidance and support.

Perceptions of Learning

Student perception of learning outcomes is an important component of self-directed learning. Simply put, if students perceive advancements in their learning, they are much more likely to maintain high levels of motivation, build confidence in problem-solving, and continue to engage in the learning process.

Figure 5 shows the responses to survey items related to student self-perceptions of learning achievement. Note that the "right skills" survey item was not introduced until the second survey. As shown in the data, students perceive their learning of "stuff," i.e., knowledge, to be lower than their learning of skills. This result is not uncommon. As reported in other studies, students in learning environments that emphasize self-direction tend to perceive that they acquire less knowledge than students in traditional, lecture-based environments.[33] Of course, this perception is *not* validated by actual examination scores. Self-perception of ability is related to student confidence and ultimately to success in self-directed environments. As such, the factors

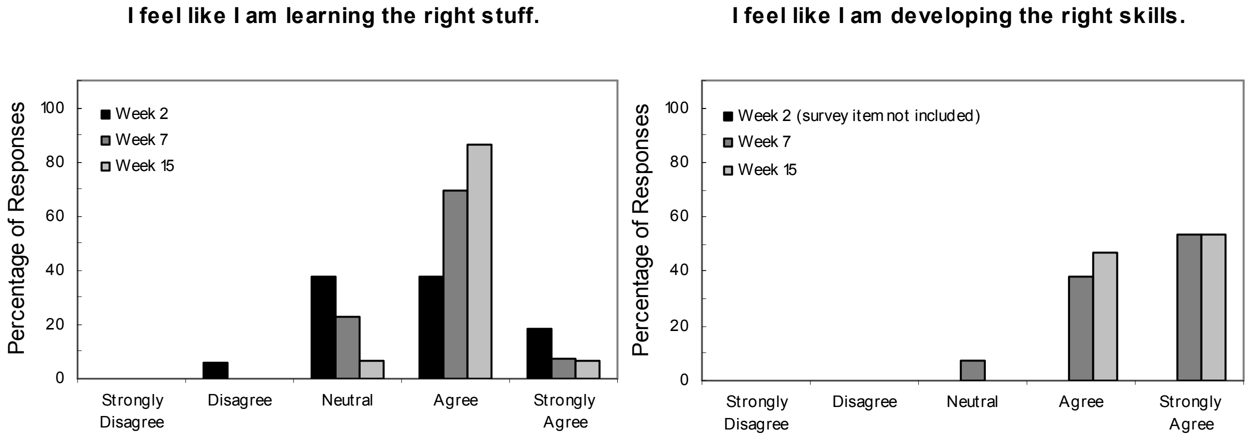

Figure 5. Student responses to survey items related to student self-perceptions of development.

responsible for any decrease in perception of knowledge acquisition should be explored and understood by learning facilitators.

Compared to their knowledge achievement perceptions, students believed that their development of skills in the materials course were higher. The high self-perceived capacity in skill areas is expected,[33] and it is entirely consistent with the materials science course's emphasis on the development of broad and transferable competencies.

Contribution to Understanding of Learning Process

An important outcome in any self-directed learning experience is an increase in students' understanding of their own learning process. As shown in Figure 6, students felt that their activities in the materials science course helped them gain insight into their own learning. As expected, the survey responses become more positive as the semester progresses and students gain more experience in self-direction and more knowledge of their needs.

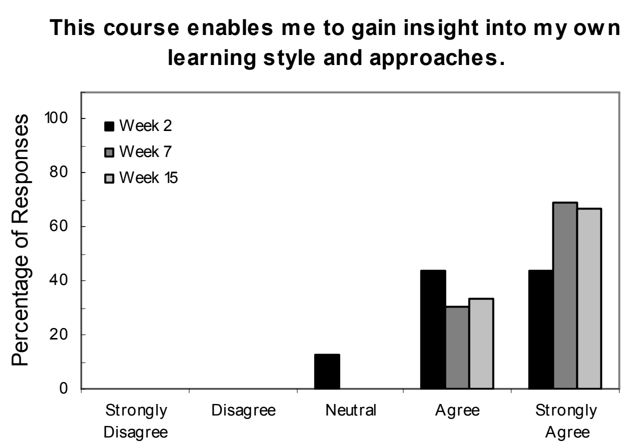

Figure 6. Student responses to survey item related to self-awareness of learning processes.

Gender Effects

An examination of gender-specific outcomes was originally intended as part of this study of self-direction. Unfortunately, the small sample size made differentiation between male and female responses difficult. A casual look at the data indicates that there is surprisingly little difference between the *average* male and female survey responses at the end of the semester, but that there may be some gender differences earlier in the semester. Given the limited data, presentation and analyses of the male and female responses would provide little value at this time. The collection and analysis of gender-specific responses will be continued in future offerings of this course; the gender-related benefits and challenges should become clearer with additional survey data and written feedback, and through individual interviews with course participants.

Conclusions

In this investigation, we used a simple course survey to explore many issues surrounding student self-directed learning in an introductory materials science course. Student responses to the survey items show the expected trends in some areas such as self-perceptions of learning achievement and self-awareness of learning process. The student responses to other characteristics of the learning environment (e.g., comfort levels and structure) provided plenty of fodder for continued discussion and future investigations, but the data on student reactions did not supply sufficient depth of understanding to yield solutions to questions regarding what instructor responses will best promote student learning.

So, how much can or should we push self-direction in introductory materials science? The answer to this question is unclear. Is it enough to attain a generally positive response from students in a self-directed learning experience or course? I would argue that it is not. Are we simply to marginalize the minority of students who express continued discomfort with self-direction? If an individual states that, "I am *really* frustrated with the project in your course, and I can't seem to make the connections that you want me to make," should I simply tell the student that he or she is atypical, and that the survey data indicate that most of the class is doing fine? Or worse, are we to write off the outliers and retain the attitude that "you can't make everyone happy?" Obviously, responses that devalue individual opinions will not create a "community of learners" or lead to improved individual learning.

One of the major difficulties in self-directed learning environments is the *individual* nature of student reactions. Broad studies that focus on data collection of student attitudes and performance may not be the answer. To be sure, large-scale, multi-institutional studies with detailed statistical analyses serve an important purpose in education. For example, they often serve to validate new learning approaches, they verify or refute anecdotal evidence and intuition, and they shed light on major issues in need of deeper investigation. Although additional broad studies will likely continue to provide insight and highlight issues regarding student learning in innovative environments, we submit that a deep understanding of student responses in self-directed learning environments may not come by way of a large-scale investigations and generation of massive amounts of numerical data.

What we desperately need is a deeper and clearer understanding of the source of student responses. We need to be able to identify the sources of student frustrations and lack of traction in self-directed environments. We seem to have a reasonable sense of *what* happens in student-directed learning, but only with understanding of *why* things happen will we be able to address the various issues that arise.

Attainment of a deep understanding of the *causes* of student reactions in different self-directed, project-based learning environments has clear benefits. The student reactions (motivation, discomfort, perceptions of learning, etc.) relate directly to both the design of learning activities and curricula, and to the development of effective methods of instructor facilitation and appropriate instructor responses to individuals. If we do not understand the causes of individual student responses, we have little hope of fostering a capacity for self-direction in those individuals.

In summary, the engineering educational community has learned some important lessons and observed some interesting phenomena in student-directed learning environments, but the answer to the "how much" question requires more work.

Future Work

We hope to continue our investigations of student responses in self-directed, project-based technical courses. Future work will be directed toward two goals. First, as noted above, the limited data generated in this study did not exhibit some expected trends in student comfort, and it did not clearly elucidate gender differences in the responses. To address these issues, we plan to measure student responses over longer times and across different courses. Anecdotal evidence suggests that students enrolled in advanced self-directed project-based courses behave differently and may have developed skills in dealing with the uncertainties and discomfort encountered in self-directed learning. An examination of the differences in student attitudes and learning processes between introductory and upper-level project courses may provide valuable insights into student development in active learning environments, and it may aid our understanding of when and how students learn to function as self-directed learners. Second, we plan to focus attention on understanding the *causes* of student discomfort in self-directed learning environments. We envision a study based on interviews with individual students who are experiencing self-directed learning for the first time, and with students who have multiple experiences in self-directed, project-based courses. We believe a clearer understanding of student responses will lead us to pedagogical approaches that address the issues underlying the responses.

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