AC 2012-5469: INTERDISCIPLINARY PEDAGOGY FOR PERVASIVE COMPUTING DESIGN PROCESSES: AN EVALUATIVE ANALYSIS

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Abstract

Developing intelligent computer products that are desirable, user-centered, and technically feasible requires interdisciplinary expertise and effective interaction across multiple disciplines. From an interdisciplinary design class that brings together students from industrial design, computer engineering, and marketing, we present an evaluative analysis of three hands-on, discipline-specific exercises designed to remove disciplinary barriers and promote cross-disciplinary appreciation.

We examine the impact of these exercises through the theoretical lens of Boix-Mansilla's construct of assessing interdisciplinarity, specifically focusing on *purposefulnnes, disciplinary grounding, advancement through integration,* and *critical awareness*. A coding system based on these criteria was expanded to include activities beyond writing and teaming processes. The resulting criteria was used to analyze transcripts of in-class team conversations and instructor facilitation. Results indicate that the interdisciplinary exercises achieved four outcomes: 1) the workshops encouraged disciplinary grounding for all the disciplines using domain knowledge from each participating discipline, 2) the workshops promoted team-level interdisciplinary integration, 3) the workshops helped students to reflect on their own choices and make more interdisciplinary decisions, and 4) the workshops provided integrative tools that led students to frame projects with interdisciplinary approaches.

Key words: interdisciplinary, teaming, design

I. Introduction

This paper focuses on evaluating the processes of interdisciplinary teaming in an undergraduate pervasive computing design course. Pervasive computing products require interdisciplinary or at least multidisciplinary approaches because, like most products, pervasive computing devices require technological functionality, user-centered form, and an adept marketing plan. In addition, pervasive computing products require design understanding of technologies that work computationally rather than mechanically, and business models that provide services more than selling a device[1]. More generally, interdisciplinary teaming is increasingly acknowledged as a skill needed in undergraduate engineering education, as evidenced by the ABET outcome of being able to work effectively in multidisciplinary teams and numerous cross-disciplinary studies, including an Oxford Handbook in 2010[2]. Our work focuses on interdisciplinary teaming in design settings, acknowledging that design is central to conceptions of engineering as a practice and to the goals of undergraduate engineering education[3].

There are few published research studies dealing with this intersection of interdisciplinary teaming, design, and engineering education where students from disciplines other than engineering are involved. Industry studies show that interdisciplinary teaming processes do not necessarily mirror traditional engineering design models. For example, Borchers' (2008) use of pattern language as a *lingua franca* in a design process that included human computer interaction (HCI), software engineers, and application domain experts (musicians, in his example) led to constructing a domain-independent design process that incorporated communication from all disciplines throughout the design[4]. Similarly, Austin et al. (2001), in their analysis of conceptual design processes in interdisciplinary teams, revealed patterns of interconnectedness between all activities and phases[5]. However, these studies were conducted in an industry setting, so the focus was more on how teams operate rather than on educating students to participate in interdisciplinary design. In engineering education, Hirsch et al. (2001) found that an interdisciplinary teaching approach combining communication and design faculty was an effective foundation for engineering freshmen[6]; however, the teams were composed of engineering students only. Likewise, Pack et al. (2004) created an interdisciplinary design experience for undergraduate engineering students, finding that their fire-fighting robot project promoted ABET educational objectives and interdisciplinary team-based education[7]. Other examples include Daems et al. (2003), which focused on early interdisciplinary education for electrical engineers intended to link subjects in a project-based design course in order to promote skills of synthesis[8]; and Hokanson et al. (2007) to instill global understandings in sustainability projects[9]. The paucity of this kind of research may be indicative of the rarity of truly interdisciplinary curricula in engineering undergraduate programs, which highlights the issues of overcoming institutional barriers, a topic not within the scope of this paper but addressed in[10].

As noted above, this paper reports evaluation results from two years of an interdisciplinary design course that included students and faculty from computer engineering, industrial design, and marketing. The interdisciplinary faculty team developed workshop modules designed to promote an integrative design process in which all students from each discipline participated in each phase. In this paper we describe three of these modules, one for each discipline, and analyze student behaviors. Each of the three exercises was based in one of the participating disciplines and led by an instructor from that discipline. However, all students participated in each exercise in order to gain not expertise, but rather insight and perspective on other disciplinary roles in the design collaboration. First, an industrial design exercise on sketching was conducted to introduce an effective means to rapidly convey ideas. "Thumbnail sketching" exercises that gave students 20 seconds to draw a prompt given by the instructor showed that everyone could draw a sketch that conveyed an idea regardless of aesthetic talent. After the sketches were complete, groups of students were asked to cluster similar sketches to show that seemingly different sketches shared meaningful underlying characteristics. Second, a marketing exercise on designing product boxes[11] was conducted to help students capture the attention of intended users and convey the values of the product. Guided by a marketing instructor and marketing students, the whole class learned techniques to consider how their products would be presented and accepted by target users. Finally, a computer engineering exercise was conducted to heighten awareness of pervasive computing products, which must sense and respond to the physical world. Led by the computer engineering instructor and students, an Arduino™ prototyping exercise was used to introduce non-computer engineering students to programming and provided "User Friendly Datasheets" to familiarize them with the abilities that each sensor provided. This exercise allowed students to learn technical aspects of the product design.

We use Boix-Manilla's definition of *interdisciplinary understanding* as "the capacity to integrate knowledge and modes of thinking in two or more disciplines or established areas of expertise to produce a cognitive advancement—such as explaining a phenomenon, solving a problem, or creating a product—in ways that would have been impossible or unlikely through single disciplinary means" [12] (p. 219). As Boix-Mansilla and co-authors explain, this sense of interdisciplinarity is based on integrative performance. In other words, interdisciplinary work brings together different perspectives into a project that has some purpose and outcome. We note two significant differences between Boix-Mansilla's approach and our work. First, Boix-Mansilla bases much of her research on written assignments that include a variety of forms such as "conceptual frameworks, graphic representations, models, metaphors, complex explanations, or solutions that result in more complex, effective, empirically grounded, or comprehensive accounts or products" (p. 225). We extend this list of communicative devices utilized in our active learning, student-centered classroom to include sketches, design prototypes, presentations, and marketing plans. Second, Boix-Mansilla focuses on individuals, targeting her rubrics to assess interdisciplinary understanding in works produced by sole authors. In adapting these assessment criteria to our purposes, we have added criteria that focus on team processes as well as products authored by multiple participants. The assessment framework that Boix-Mansilla offers includes four criteria: purposefulness, disciplinary grounding, advancement through integration, and critical awareness. These criteria, along with our adaptations for coding, are described in Table 1 and discussed in the Methods section (III).

In the following sections we describe the discipline-based workshops that have been designed to promote interdisciplinary understanding. We then explain the methods used to collect and analyze data from implementation of the modules in two courses. The following results section describes patterns emerging from student interactions in each type of workshop. We conclude with a discussion of the limitations and effectiveness of the workshops.

II. Discipline-based Workshops to Promote Interdisciplinary Understanding

Results from previous offerings of this class indicated that there was a need for additional interventions that would help students deeply engage in interdisciplinary processes by facilitating more balanced cross-disciplinary collaborations. According to the theoretical framework of interdisciplinary work by Boix-Mansilla[12, 13], interdisciplinarity is fulfilled when purposefulness, disciplinary grounding, advancement through integration, and critical awareness are all present. Hence, we carefully developed hands-on exercises dedicated to each participating discipline. They were designed to help students 1) frame the project with an interdisciplinary, user-centered approach and address multiple audiences, 2) gain conceptual knowledge from and deepen appreciation of each participating discipline, 3) promote innovative processes and products by alternating leadership roles across disciplines in the team-based design process, and 4) enhance awareness of the need for interdisciplinary collaboration.

Three discipline-based workshops were administered during the semester, including the topic research (week 2), concept development (week 8), and feature development phases (week 11) of the design. The first workshop was the *Thumbnail Sketching Exercise*, an industrial design workshop that required all students to draw a sketch in just 20 seconds that conveyed ideas ranging from a simple object to a complex concept. The second workshop was the *Product Box Exercise*[11], a marketing workshop that asked students to design packaging for their final products to encourage students to think about how their products will be perceived/received by consumers early in the process. The third workshop was the *Arduino TM Prototyping Exercise*, an electrical & computer engineering workshop that taught students how to find pervasive computing design opportunities with simple sensors and output devices. More detailed descriptions of these workshops can be found in [Authors][1].

The workshops had several major benefits according to the criteria. First, the workshops provided disciplinary grounding for all the disciplines using domain knowledge from each participating discipline. For example, the industrial design workshop demonstrated that sketching is a powerful tool that anyone can use to convey ideas. Second, the workshops promoted team-level interdisciplinary integrations. By providing opportunities to create integrative knowledge across disciplines and allowing students from each discipline to mentor the others, the workshops encouraged deeper appreciation among students. Third, the workshops helped students to reflect on their own choices and make more interdisciplinary decisions. Instructors cued students to reflect on their team processes so that they could actively account for each disciplinary perspective at every step. Fourth, the workshops provided integrative tools that led students to frame projects with interdisciplinary approaches. The workshops showed students that they could learn and adopt other disciplines' methods to develop an innovative device for an identified user group.

III. Methods

A. Setting and Participants

This was a semester-long, team-based, project-focused interdisciplinary design course that was cross-listed as a senior-level class in three different departments: industrial design (ID), marketing (MKT), and electrical and computer engineering (ECE). For this study, we used the data from two consecutive offerings of this course, Fall 2010 and Fall 2011. The same interdisciplinary team of three instructors (1 ID, 1 MKT, & 1 ECE) led the class for both years. During 2010, a total of 21 students (7 from each discipline) participated. During 2011, a total of 20 students (7 ID, 6 MKT, 7 ECE) participated. All of the students were seniors and their ages ranged from 19 to 22. The main intervention for the course was the discipline-based workshops explained in Section II. The ID workshop was administered during the second week, the MKT workshop during the eighth week, and the ECE workshop during the eleventh week.

Table 1. Criteria for assessing interdisciplinary understanding and teamwork.

	Boix-Mansilla *et al.* **Definition**	Authors' **Additions for Teamwork**
Purposefulness	Clarity about the aims and audience of the students' work: • Clear goals • Explicit rationale for interdisciplinary approach • Viable scope • Use of purpose to reason and make choices • Work addresses multiple audiences (2007, pp 228-9; 2009, p 342)	• Identify and address needs of potential users • Frame design problem integratively • Map the value of disciplinary inputs to steps in the design process • Communicate design processes, problems and decisions to each other
Disciplinary Grounding	Carefully *selected* and *appropriate* use of disciplinary practices: • Theories • Findings • Examples • Methods • Validation criteria • Genres • Forms of communication (2007, p 222)	• Adopt roles as experts in home discipline • Do work in other disciplines • Communicate knowledge using other disciplinary methods
Advancement through Integration	Advancing student understanding by use of integrative devices such as: • Conceptual frameworks • Graphic representations • Models • Metaphors • Complex explanations • Solutions Results in the form of more complex, effective, empirically grounded, or comprehensive accounts or products. (2007, p 225)	• "Studio" critiques • presentations • Marketing plans • Programming kits • Sketching/white-boards • Prototypes Processes take form of stages that are disciplinarily inclusive and multi-layered
Critical Awareness	Evidence of reflective self-critique about interdisciplinary work including: • Choices • Opportunities • Compromises • Limitations (2007, p 228)	• Create and implement collaborative timelines • Account for each disciplinary perspective at each step

The previous definition of interdisciplinary teamwork focused on assessment of interdisciplinary writing, therefore it did not account for dynamics of collaborative behaviors. In the context of interdisciplinary team design, communication and collaborative behaviors among team members play key roles in judging the success of interdisciplinary processes. To account for the gap, we added descriptions of team behaviors that are associated with each criterion of interdisciplinary work.

B. Data Collection and Analysis

This study was fully reviewed and approved by [Institution's] institutional review board. The participants reviewed and signed informed consent forms during the first class of the semester. The researchers observed and video-recorded all of the class sessions. The video-recordings were reviewed with a focus on design communications and student team behaviors for qualitative content analysis.

IV. Results

The workshops, focused on discipline-oriented processes, helped students gain *purposeful* clarity about why their design goals required an interdisciplinary approach. In terms of *disciplinary grounding*, the workshops situated students as experts in their home disciplines while simultaneously offering students opportunities to work in other disciplines—adopting knowledge and authority—and to communicate ideas using cross-disciplinary methods and language. The workshops also were effective tools in helping students create processes and products that would not have otherwise emerged in single discipline settings. This *advancement through integration* resulted in innovative final projects and a design process in which multiple disciplines were involved at each step, with leadership alternating between disciplines. Finally, the workshops also promoted *critical awareness* of the opportunities and limitations of interdisciplinary work. By learning about the methods used by other disciplines, students also gained enough knowledge to engage in directed brainstorming and were able to negotiate feasible timelines and work schedules.

A. Thumbnail Sketching Workshop

Instructors provided disciplinary knowledge in the beginning of the workshop that set the tone for disciplinary grounding in which some students would be experts but that even non-expert students could use methods from other disciplines. For example, an ID instructor explained that the purpose of the Thumbnail Sketching exercise was to ensure that both ID and non-ID students could do it: "In 20 seconds, there is not going to be any time except to communicate the idea…You get to abandon judgment whether or not it is a good drawing or not." In this activity, students had the opportunity to do work using another disciplinary method, and they were also introduced to other ways of thinking. After many drawings of apples resulted in apples with a leaf on the stem, the ID instructor challenged students to think about how ideas are communicated through visual means:

> "How many of you have recently bought apples that had leaves on them? One of the things that we do is that we tap into existing memories and we go in with pre-

> conceived notions that can be both beneficial and negative. They might not be productive or they can be opening up new opportunities."

The instructors also provided quick feedback during the exercises in an effort to motivate students to enhance their interdisciplinary efforts. For instance, the ECE instructor evaluated the class effort after the thumbnail sketching exercise by saying, "The point is you were still able to get the concept across even within 20 seconds. The point of sketching is that you can get this image out of your head and put it on the table so that we can see and then you and I can have a conversation about it." This remark was highlighting the usefulness of an ID method for the interdisciplinary project that they were going to work on for the rest of the semester. By explaining the importance of sketching to communication in the design process, the instructor helped students understand why interdisciplinarity is necessary for the type of project that they were engaged in (*purposefulness*). Later in the semester, student teams used simple sketching as their means of communication to convey design ideas, and sketching was not limited to only ID students.

Although early in the semester, this workshop helped students to achieve *critical awareness* of the issues at hand as well as appreciation of other disciplines. For example, referring to clustering the sketches with similar characteristics into categories after all the sketches were complete, one ID student was encouraged to reflect on his experience during the ID workshop, saying:

> "Once we split up, as a group we decided that there should be sub-categories within categories to simplify even more or explain further, but *that's not something I personally would have come up with on my own*. So that was totally something that changed. Not only does it have now a horizontal direction, now it has a vertical direction as well."

In this remark, the student presents a reflective self-assessment of the work he had just completed. That is, he was aware of the importance of the interdisciplinary processes and was able to realize that he expanded beyond his own limit through collaboration with others.

B. Product Box Workshop

The marketing workshop activity involved having students use a variety of materials to construct packaging for their products. The MKT instructor started off the activity by situating each student as a competent marketer: "What we're asking you to do is be yourself, be an astute marketer, product designer and engineer, and also, at the same time, to be your own consumer."

This marketing activity helped promote *disciplinary grounding* by having students adopt knowledge and communicate knowledge using other disciplinary methods. For example, when pressed to think through the marketing aspect of designing a package for his team's product, an ECE student described not only the physical design of the box, but also the multiple audiences that the package could appeal to. Asked about how much information the package would need to provide in order to give consumers a true understanding of the product, he responded:

> "A lot. That's why we went with a descriptive back and sophisticated looking front, because it's not going to be very cheap, we want them to think it's advanced and cool. We looked at some DSs and things and see what they were packaging, and they liked the black/silver combo, like whites and silvers and black makes it seem like you're getting something that's really classy and advanced. So this is some advanced technology, and that's why it's black."

The student is describing a type of package that appeals to both kids (the end user) and parents (the buyer).

Disciplinary grounding was also shown in students' explicitly expressing appreciation of other disciplines. For instance, during a design conversation that occurred one week after the product box exercise, ID and MKT students asked ECE students in the team how cloud computing worked. The ECE student explained how data could be stored in servers and accessed over the Internet. At the end of the conversation, one ID student said, "Okay, I trust you engineers." In this case, the ID and MKT students framed the ECE students as domain knowledge experts and asked them for information. The ECE students were capable of providing satisfactory information, which earned them their teammates' trust. Referring to the ECE students as 'engineers' and saying that he or she trusted them highlighted appreciation and trust towards the person from another discipline that he or she developed during the process. This type of consulting behavior also occurred during the ECE workshop later in the semester.

The teamwork that occurred during this activity also promoted *advancement through integration* (noted by cross-disciplinary participation). For example, during the product box exercise, one of the teams, led by a marketing student, developed their slogan.

> MKT: Okay…how about- 'Power in Your Hands?'
>
> ECE: Let's write them all up and see…
>
> ID: Our slogan?
>
> MKT: Yeah. Like, with our system, you power the individual.
>
> ECE: Right.
>
> [ID student gets up, goes to the board and writes "Empowerment: 'Power in Your Hands.']
>
> ECE: For me, the biggest thing is how can we relate what I'm doing to how I'm affecting my bill. More importantly, I think people would buy it for more than just some money value and saving. Something like…'Connect with the Earth,' something like that.

In this conversation, the MKT student is leading the activity by suggesting a slogan and explaining values conveyed in the slogan. This is an indication of *disciplinary grounding*, since a MKT student is assuming a leader role during a MKT workshop. After the MKT student's initiated the action (producing a slogan), an ID student takes the idea and names the value that the MKT student just explained. An ECE student follows with an additional opinion on the value their product provides. From the conversation, it is shown that every student is engaged in the marketing process of positioning their product. In order to achieve that goal, the students are using a slogan that will convey the value of the product as an integrative device.

Additionally, students demonstrated *critical awareness* of the value of other disciplinary perspectives. For example, an ECE student agreed with an ID student who said: "I kept the box. It just felt like- I can't throw this away, because it's going to be worth something." Even though they do not have an immediate use for the results of the workshop activity, they are reflecting on the potential value of this step in the design process—a step oriented in a discipline other than their own.

C. Arduino™ Kit Workshop

The Arduino™ prototyping workshop helped students in both courses achieve all four learning objectives. In 2010, the instructor described the workshop as "a detour" in which the ID and Marketing students "would get an idea of what simple coding can do." While students stayed in their product design groups, the focus was turned toward a discipline-oriented process, with the Arduino™ kit serving as an integrative device that resulted in *advancement through integration*. Students were instructed to "play" with the kits, to "come up with different ways to use it," and to make it do something "beyond what we programmed it to do." While non-ECE students at first shied away from the devices, handling the kit like it was "fragile" and saying "whoa, whoa—I don't understand!" they were soon playing with it, handing it back and forth, and even taping it to a cardboard prototype. Within an hour, student groups were able to learn about opportunities of basic programming and sensors, brainstorm various applications and start to work on several creative ideas, such as a Marco Polo game, an electronic musical instrument, and a "painting sound" game. One team created a virtual birthday gift box that played the "Happy Birthday" song when opened and with "candle" lights that a user could virtually "blow out." Such ideas were innovative advances that resulted from integrative, interdisciplinary teaming.

The sensor workshop also promoted *disciplinary grounding*. The ECE students were given the kits with instructions, then immediately began explaining the components in the kit to their team members. In other research on engineering students in interdisciplinary teams[14], engineering students have complained about having to "dumb down" their work in order for others to understand. In this case, ECE students were introducing technical vocabulary and incorporating non-ECE students into the programming tasks:

> "It's not storing now, for now it just runs sequentially, so after this line, it goes to the next and once that's done, it comes back up the top. What it's trying to do right now is- making a variable called x, and it's assigning x to the output, um, whatever this one over here is. So when you have the parenthesis, it's calling up a function, and this function is returning values."

As ECE students described the functionality of the kit and the coding process, non-ECE students responded with questions like “Is this a sensor?” (testing a specific component for response) and “Does it store the values?” Although the non-ECE students did not become programmers (this was not the objective), they did adopt knowledgeable participant roles. For example, in order to help, an ID student asked about the breadboard, “Does it matter what direction these things go into?” Likewise, a marketing student helped to develop the code by finding musical notes for “Happy Birthday” and translating them into the numerical values necessary for the tone generator included in the kit. In terms of technical knowledge, every student had the opportunity to learn about the functionality of an accelerometer through a combination of listening to a resident expert (the ECE student on their team) and interactively creating a new use for the sensors.

Through this learning experience, the students also reflected on the interdisciplinary character of the work, though this learning objective of *critical awareness* was seen more clearly in their work on their own projects later in the semester. There were many questions directed to the resident experts that revealed limitations of the sensors, such as “Can you record it?” and “Can the sensor and the LED do the same thing at the same time?” These questions heightened awareness of what the device could and couldn’t do, and also made students aware that interdisciplinary design required time and communication across knowledge domains.

The instructors repeatedly emphasized that the *purpose* of the course was for students to develop as interdisciplinary team members and learn about benefits through experiences. For instance, the ECE instructor told the students, “Part of our motivation for doing this is not just reducing energy consumption in residences. It’s getting you to understand, have contributions as a team that you wouldn’t have been able to make individually.” It led students to actively reflect on what they were learning from the processes. Students were able to gain in-depth insights into interdisciplinary design processes and encouraged them to adopt more integrative approaches for their projects.

Finally, students also gained the ability to clearly assess the interdisciplinary work in a *purposeful* way. As one ID student noted in 2010:

> “I think what's important is that sensors are- we can't set them. And the outputs, you can't read them. You can't read from the LED, and you can't say- You can't tell this. If I were to write to the range meter, hey I want you to say there's something in 20 ft away. It can't do that.”

While realizing limitations of the sensor kit, the student is also beginning to deeply understand the idea of pervasive computing. That is, the intelligent devices the students are designing are not meant to interface with users like typical computers—the devices must operate cohesively within the human environment.

V. Conclusions

Expanding from Boix-Mansilla’s criteria of assessment for interdisciplinary student work, we designed discipline-based workshops for an interdisciplinary pervasive computing design class to promote cross-disciplinary collaborations among students and teach them to become better interdisciplinary thinkers. The guiding criteria for the workshop design were purposefulness, disciplinary grounding, advancement through integration, and critical awareness. Examining the qualitative data from two offerings of the course in 2010 and 2011, it was shown that the workshops effectively fostered interdisciplinary teaming processes, which led to achievement of original goals of this course.

The importance of interdisciplinary team design comes from bringing disciplinary lenses together. To catalyze this process, the workshops are integrated into the design processes throughout the semester. Different methods of *'designing'* a product are integrated into a design process in which each discipline is included in each step and in which leadership alternates between disciplines.

During the workshops, the students showed flexible leadership yet active engagement in all three workshops. Because every member of the team had a chance to become a domain knowledge expert for the team activity and mentor others, the teams not only gained knowledge from the workshops but also developed deep level of appreciation of other disciplines, which is a key to a successful interdisciplinary team. Also, students asked for guidance from other *disciplinary experts* and collaborated with each other instead of dividing the work into disciplinary pieces and assigning the member from the relevant discipline to do the piece. Reflective questions that instructors provided during the workshops led the students to be aware that the interdisciplinary processes were as important as the quality of the product that they produced.

Bringing disciplinary lenses together through discipline-based workshop successfully fostered interdisciplinarity in student design teams. Students from all the disciplines were engaged in the whole process from the beginning, allowing continuous inputs that prevented delays due to recycling through the process. This integrative model of design led to 1) cross-functional awareness of other disciplinary roles in the design project, 2) identification of constraints that apply to the whole project (e.g., technical feasibility, cost analyses, and design limits in terms of form and function/usability); and 3) construction of more accurate and reachable timelines.

The four guiding criteria of interdisciplinary work (purposefulness, disciplinary grounding, advancement through integration, and critical awareness) lend useful insights into appropriate assessment questions. In terms of assessment, purposefulness and critical awareness seeks similar qualities; hence, we combined the two criteria into one. In the section below, we ask assessment questions of interdisciplinary design work for each category and answer it in terms of student team processes and final outcome (products) of the courses.

A. Disciplinary grounding

Assessment Question 1: Are the selected disciplines appropriate to inform the issue at hand?

To be commercially successful, pervasive computing products must have a balance of technical, physical, and economic constraints. The three disciplines selected for this pervasive computing design course were capable of fully accounting for those constraints. In addition, the complexity of pervasive computing products is such that they must be developed by a team of professionals, and those professionals must have an appreciation for the full range of design constraints faced by the product. That appreciation is all too often gained by happenstance after a student has graduated and entered the workforce. Bringing students from electrical & computer engineering, industrial design, and marketing into one class was an adequate setting for addressing this issue.

Assessment Question 2: Are any key perspectives or disciplinary insights missing?

Even though this course brought a full spectrum of disciplinary insights that includes design, engineering, and business, it was limited to only one semester. The students were able to conceive and develop product concepts and even built rough prototypes with some presentation of electronic functionality within the semester. However, a second semester would help us better understand different stages of product design cycles where technological devices are built, marketing plan is refined, and form is fitted to device. We recognize that this course is occurring in an idealized academic environment, so teams stay interdisciplinary at stages where teams would probably split in industry. However, being in interdisciplinary teams throughout the entire product design process could be excellent training to increase knowledge and appreciation of other team members' roles.

Assessment Question 3: Are the considered disciplinary theories, examples, findings, methods, and forms of communication accurately employed, or does the work exhibit misconceptions?

Throughout the course, different communication modes (e.g., sketching, programming), design methods (e.g., storyboarding, electronic prototyping), and theories to understand user and consumer behaviors (e.g., Maslow's hierarchy of needs, value propositions) were employed to guide students through the process. The students learned the methods that were outside their disciplines and used them at a basic level. The level of utilization of these methods and tools was not comprehensive, and it was not our intention for students to become experts in disciplines outside of their own. Instead, it helped students understand the processes and design knowledge involved in other disciplines, which led them to become more effective interdisciplinary team members.

B. Advancement through integration

Assessment questions: Is there evidence of disciplinary integration (e.g., conceptual framework, graphic representation, model, leading metaphor, complex explanation, or solution to a problem)? Is there evidence that understanding has been enriched by the integration of different disciplinary insights?

All three workshops and materials were carefully designed so that they can serve as integrative devices throughout the course. While participating in a workshop for one's own discipline, the students were required to lead the team through the activity. Because of this alternating, flexible leadership structure of the team, the members were called upon to explain concepts, methods, and metaphors in a way that people outside their disciplines could understand. This practice of peer mentoring not only promoted cross-disciplinary communications, but also enriched understanding of the process by integrating different disciplinary perspectives.

C. Critical awareness and Purposefulness

Assessment question 1: Does the work show a clear sense of purpose, framing the issue in ways that invite an interdisciplinary approach?

Critical awareness and purposefulness are exhibited by reflective behaviors of students such as expressing appreciation for different disciplines or accounting for interdisciplinary inputs. The instructors designed the course interventions in a way that ensured balanced participation of all disciplines. Because the main project for the course falls under the category of product design, unless students are purposefully introduced to all disciplinary perspectives, the process is likely to become either an ID process or a typical "throw-it-over-the-wall" multi-disciplinary approach. With undergraduates at our institution, it was our experience that industrial design students have a very specific idea of what design is, have experience in design, and do not realize there are other aspects of design. On the other hand, ECE students have very little experience in collaborative design but do realize what importance of engineering expertise has on product design, even though they are not often aware of other design processes. In addition, marketing students think of designing posters or product campaigns, and do not realize that they can make critical contributions to a technical product design process. In order to achieve an interdisciplinary experience for students, we designed the course interventions to help students frame the project as a cycle of integrated phases. Additionally, we framed the project as an entrepreneurship project to further emphasize the need for interdisciplinary effort.

Assessment Question 2: Is there evidence of reflectiveness about the choices, opportunities, compromises, and limitations involved in interdisciplinary work and about the limitations of the work as a whole?

The reflective conversations occurred throughout the courses both naturally and by prompts from instructors. Students often talked about how they were led to a design (form) choice to account for an engineering feasibility issue or customer preferences. This is evidence of students being aware of the interdisciplinary inputs affecting their design processes. Students also reflected on experiences in which they had reached beyond their own comfort zones and expanded their perspectives. Instructors took a meta-cognitive approach and often prompted this type of reflection during the class. Especially during 2011, the instructors purposefully explained the purpose of activities they employed in the class so that students are aware of what they are expected to learn during the exercises. The instructors also prompted students to reflect on interdisciplinary processes and learning experiences throughout the course. This helped students to further understand the benefits of participating in interdisciplinary processes and appreciate the presence of other disciplines in the project.

In conclusion, assessing interdisciplinary design work is a difficult challenge because of its complexity stemming from involving many different fields for one project. Also, in an educational setting such as an integrative design course, we should also assess interdisciplinary team processes as well as final products. This paper argues that pedagogical approaches that promote interdisciplinary outcomes should strive for a balance of disciplinary perspectives and integrated processes.

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