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Smart Surfaces: a Multidisciplinary, Hands-on, Think-tank

New design practices are emerging that span multiple traditional disciplinary boundaries. As these new models of practice manifest, new pedagogies also become necessary, often challenging both existing educational models and institutional constraints as a result. Gibbons, et al[1] questioned the adequacy of traditional disciplinary structures within universities in the context of broader social, technological and economic contexts. The Association of American Colleges and Universities have argued that universities need to change their practices to develop students as "…*integrative thinkers who can see connections in seemingly disparate information and draw on a wide range of knowledge to make decisions*."[2] The National Academies have recommended, "…*students should seek out interdisciplinary experiences, such as courses at the interfaces of traditional disciplines*…"[3] and that "…*schools introduce interdisciplinary learning in the undergraduate environment, rather than having it as an exclusive feature of the graduate programs*."[4] As indicated above, there has been much calling for cross-disciplinarity in education but to date there has been little investigation on the impact of cross-disciplinary courses on learning, especially in comparison to teaching that is more discipline-specific. For educators a central question arises: How do we prepare students to be extra-disciplinary thinkers and doers with "*habits of mind*"[5] that prepare them to make the sort of hybrid responses that complex performance problems demand?[6]

Since the Fall of 2005, the University of Michigan has dedicated $2.5 million dollars to support team-teaching efforts and cross-disciplinary degree programs at the undergraduate level through the Multidisciplinary Learning and Team Teaching (MLTT) Initiative. This initiative has sought to address the belief that integrative learning should be a key component of the undergraduate experience and acknowledges indications that cross-disciplinary study is a key to this process. The authors were awarded funding from the MLTT Initiative to absorb some of the risk involved in the creation of the 'SmartSurfaces' course during its first two years, supporting all of the design-build-test activities employed. 'SmartSurfaces' is a 3 credit, cross-disciplinary studio course that is team taught by the authors - professors from different university units (Art & Design, Materials Science & Engineering and Architecture). The enrolled students so far have been junior and senior undergraduates from these same three units. The course has been offered twice previously (Fall 2009 and Fall 2010) and is at the time of writing entering its third year. The University of Michigan Center for Research on Learning and Teaching (CRLT) conducted surveys of students who had enrolled in all fourteen MLTT-funded courses. The responses of the students from 'SmartSurfaces' show profound increases in communication, creative thinking and critical thinking over the other courses. The purpose of this paper is to develop an understanding of how the design and implementation of this course as a making-driven instantiation of 'problem-based learning'[7] is related to these outcomes.

COURSE DESIGN

'SmartSurfaces' offers a cross-disciplinary, project-based learning experience in which twenty-four undergraduate students form teams to build physical systems and structural surfaces that have the capability to adapt to information and environmental conditions. Central to this is a project-driven pursuit of solutions to 'under-defined problems'. This 'under-definition' allows personal ownership of the learning process to be developed by the students. Once in the course the students are divided into four teams of six. Each team has two Art & Design, two Materials Science & Engineering and two Architecture students on it. The twenty-four students and three professors meet once a week for six hours. In addition, the student teams have to meet outside of class to work on their projects.

The course is listed in each unit's offerings as a separate catalog number. However, the course utilizes a collaborative, team-teaching model - all three professors attend each class period. They advise, critique and contribute to all team projects. In this way the faculty role is to facilitate student progress, to help identify any problems, set goals and to evaluate the progress of the teams and individual students through the semester. The professors provide instruction through various methods including lectures, hands-on demonstrations, and by offering criticism of student projects and presentations. The faculty believes this 'three-headed monster' approach encourages the use of higher order thinking skills and promotes meaningful learning. For example, contradictory advice from and open disagreement between the professors causes the students to grapple with the decision of which advice is best, if any. In other courses many students approach assignments by trying to work out "*what the Professor wants.*" In the case of 'SmartSurfaces' this is pointless, as each professor values different aspects of any given project. Correspondingly, everyone is encouraged to be generous with her or his feedback and advice and to not hold back in discussions.

The course is organized into two phases. For the first phase, participants focus on problem and constraint definition, structured brainstorming and skill building. The second half of the semester involves the production of fully realized funded projects (each team receives $3,000 US). In this final phase of this course the students have to think of and construct arguments about what the most valuable problem to tackle might be (within some loose constraints). Visiting lecturers, specialists, site visits and relevant stakeholder organizations are enlisted to expand the scope of the course. There are weekly assignments, specifying due dates, required documentation and deliverables.

Phase 1

For the first six weeks the teams build specific skills in: microcontroller programming (Arduino), parametric modeling (Digital Project), digital fabrication, and cross-disciplinary collaboration. During this initial skill-building phase the student teams are required to undertake assignments where the project briefs demand both 'top-down' (deterministic) and 'bottom-up' (stochastic) making strategies. The 'top-down' approach is where the students are given a specific challenge (e.g. "*create a 2 axis,* *solar tracking, smartsurface*"). In this approach the question "*why are we building this?*" is most often deferred or remains unasked. This 'top-down' approach emphasizes planning and a complete understanding of the specified system. This approach, however, runs the risk that systems may be built without having a clear idea of why this might be necessary or valuable - other than to satisfy the professors.

The 'bottom-up' project approach is the piecing together of subsystems or components to give rise to more complex systems (e.g. "*here is a pile of components - what can you do with them?*"). In the 'bottom-up' approach inevitably the available parts are 'played with' and some of them linked together to form subsystems, which then in turn are connected until a complex system is formed. In this approach function emerges from experimentation and the students are more likely to have to negotiate the question "*why are we building this?*" and to determine relative values based on each individual's goals (in concert with their peers). Communication and negotiation are necessary to determine the functionality that is to be achieved by this type of project.

Positive aspects of the 'top-down' approach are that it is efficient - the students know when they are 'done' and if they got it 'right' (i.e. "*does it work?*"). The 'bottom-up' approach is more ambiguous and inefficient but allows for more opportunity for each individual (or no individual, as the case may be) to assert his or her own point of view. Of course, this discussion over-simplifies what actually happens during the course of these projects and both assignments result in some form of a hybrid 'top-down-bottom-up' process. However, the goal here is that the students have an opportunity to experience multiple approaches to working that may not be typical in their university unit, pick up new skills, learn new vocabulary and recognize differences and/or similarities in ways to working, thinking and communicating among their peers and faculty before they begin the second phase of the course.

Phase 2

During the remaining part of the semester the teams focus on the production of a fully realized design project as an application of the knowledge gained in Phase 1, relying on cross-disciplinary, collective effort to carry out the project. Each team is required to design, build, program and test an 'X-SmartSurface' where "X" is a changing modifier. Previously, "X" = "Heliotropic" (Fall 2009) and "Biomimetic" (Fall 2010). All participants (including the professors) have to consider what constitutes a "surface"; what might make one "smart"; and what are the appropriate tools, resources and knowledge necessary to go about making one. For example, in Fall 2010 each team was required to design, build, program and test a 'Heliotropic SmartSurface'. Each team was required to produce something between the size of a tabletop and a minivan - a fully functioning unit or a functioning model at scale to be presented in a gallery setting with each team having open floor space for a self supporting element and 8' x 8' of available wall space to include supporting diagrams, renderings, process, etc.

COURSE IMPLEMENTATION

Each week the teams are expected to produce at least one physical prototype, give a group presentation on what they have made and how they went about doing this. Each individual is also required to keep a blog documenting his or her own contributions. Each week the students present either a completed project or describe the progress they have made for multi-week projects. These team presentations are viewed by the professors, the other students and often by invited guests. Each team is asked to explain aspects of their design, their assumptions about the design and its context, use or purpose and they are asked to talk about their experiences working in their cross-disciplinary teams. At these presentations there is an expectation that any device presented must function. The presentations are followed by an extensive critique, which includes questions from the instructors, invited guests, and fellow students. The questions from the different professors and students often illustrate different priorities, values, preconceptions and preferences. The student teams are expected to synthesize the multiplicity of feedback and improve their designs and their discourse about their designs. Assessment of student performance occurs via evaluation of the weekly team presentations, prototypes, individual blogs and the final project. At the end of the course, each team is also required to produce a project report (15 pages minimum). This report is intended to present the knowledge and understanding assimilated by the students during the semester.

In 'SmartSurfaces' we have made it a requirement for the teams to reflect on what has been valuable or difficult in their interactions. Several times during the semester each student is required to complete a Comprehensive Assessment for Team Member Effectiveness (CATME) online survey to evaluate themselves and their teammates.[8] In this survey there are five aspects of teamwork to be rated on a five-point scale (under the headings: Contributing to the Team's Work; Interacting with Teammates; Keeping the Team on Track; Expecting Quality; and Having Related Knowledge, Skills, and Abilities). Each team is also required to establish a strategic framework in the form of a written contract[9] establishing the team's mission, vision, values and goals. A group calendar is also required that makes them consider what is realistically possible with the time and human resources available. They need to specify the roles each team member will have and importantly, how they will manage conflict. Each individual must decide whether to specialize or take a more general role based on their abilities, aptitudes and their team's needs. Every participant is expected have different (and evolving) levels of skill and experience before, during and beyond the course.

'SmartSurfaces' meets in the neutral territory of Design Lab One (DL1) in the James and Anne Duderstadt Center on the University of Michigan North Campus. Therefore no students have the advantage of being on 'home turf'. DL1 is a 2,500 square foot room designed specifically to support collaboration and peer learning. DL1 is a highly versatile space and collection of resources that greatly facilitate the collaborative process. This space is more than adequate for 'SmartSurfaces' class meetings, presentations and tabletop prototyping but the course also requires students to seek out more specialized equipment and space to build their final projects. The students therefore have to be resourceful and take the initiative to secure admittance to the facilities they want or need to get in order to complete their projects.

University of Michigan is rich in physical and human resources, which more often than not are organized and accessed through discipline-specific channels – people, space, equipment and knowledge are arranged and stored in schools and colleges. We wanted our course to operate as a framework that promotes or indeed requires broader access to facilities and supports the development of knowledge transfer between units. To emphasize this approach, at the beginning of the semester all students are given a tour of the various facilities available through the participating units. The students are made aware of the requirements to access this equipment and space (e.g. training sessions) but it is impressed upon them that they are responsible to make the time to get up to speed on equipment they might be interested in using. In practice, the students that have made use of a piece of equipment or process show others on their team how to use it. In this way new skills are introduced through project-led learning and this knowledge is transferred from peer to peer. We point out that the course is not about everyone learning everything to the same extent - but that there is a real opportunity to acquire skills, knowledge and experience with a wide range of tools and applications.

RESULTS

In the summers of 2009 and 2010, the Center for Research on Learning and Teaching (CRLT) conducted surveys of students who had enrolled in MLTT-funded courses over the previous two years.[10] The survey elicited students' self-reports of their learning through question sets with rating scales. The students were asked to compare the skills they developed in MLTT-funded courses with their learning in other University of Michigan courses. These skills included critical, analytical and problem-solving skills; communication and collaboration skills; and creative thinking skills. Invitations to participate in the online survey were sent to 634 individuals. Overall, 417 participated across the 14 courses, for an aggregate response rate of 66%. Of those who started the survey, 88% completed it. For individual courses, the response rate was never less than half, with the range of response rates being 51% to 78%. Table 1 (below) compares the percentage of participants in the 'SmartSurfaces' (SS) course surveyed that indicated greater learning gains more or much more than in their other University of Michigan courses compared to the mean responses from the other Multidisciplinary learning and Team Teaching Initiative (MLTT) courses.

The survey results from the 'SmartSurfaces' students have been described by the Associate Director of CRLT as "*Off the chart.*"[11] From the results above it is clear that this model of undergraduate education is capable of producing profound experiences. We believe the design and implementation of this course is related to these outcomes. The course gives the students the opportunity to think critically, analyze and tackle complex, real-world problems. They must

1. How much did you develop the following skills during this course?	**MLTT**	**SS**	**+/-**
Drawing on multiple perspectives in addressing problems or issues	82%	91.6%	9.6%
Making connections between major concepts from different fields of study	82%	100	18%
Identifying the components of a problem or issue	70%	91.7%	21.7%
Identifying the data needed to solve a problem or answer a question	58%	75%	17%
Investigating complex systems	68%	83.3%	15.3%
Formulating good questions	70%	75%	5%
Choosing the appropriate method (or mixture of methods) to solve a problem	62%	72.8%	10.8%
Clarifying an unstructured problem	67%	100%	33%
Considering a broader context when decision-making and problem-solving	84%	100%	16%
2. How much did you develop the following skills during this course?	**MLTT**	**SS**	**+/-**
Identifying multiple perspectives when listening or working with a group	63%	91.7%	28.7%
Participating effectively in group discussion	52%	100%	48%
Conveying your ideas effectively	55%	91.7%	36.7%
Checking to see if your thoughts are understood	47%	100%	53%
Checking to see if you understand others' thoughts	50%	100%	50%
Relating to people with backgrounds different from yours	58%	100%	42%
Listening to audio or video media critically*	52%	16.6%	-35.4%
3. How much did you develop the following skills during this course?	**MLTT**	**SS**	**+/-**
Willing to change your mind	70%	91.7%	21.7%
Being open to others' points of view	66%	91.6%	25.6%
Planning	46%	91.6%	45.6%
Analyzing problems in a way that considers unusual alternatives	74%	100%	26%
Working through obstacles	59%	100%	41%
Being able to critique others	53%	91.7%	38.7%
Being able to receive feedback and criticism	56%	100%	44%
Producing work of your own design	57%	75%	18%

*Table 1: Comparison of the results from 'SmartSurfaces' students with the mean responses from students of other MLTT courses. Questions were asked about (1.) critical thinking skills, (2.) communication skills and (3.) creative thinking skills. *Activity not engaged in during 'SmartSurfaces'.*

find, evaluate, and use appropriate resources from the wide array made available to them from across three university units. In order to work collectively they must develop effective communication skills and become dexterous in the selection and application of content knowledge. Collaboration or at least cooperation is a necessity and self and peer assessment is conducted and presented back to the students repeatedly throughout the semester. Each discipline has different core assumptions and goals - so for the teams to become effective, they must develop shared values and a common working culture. The experience of conflict resolution and an increased tolerance of frustration are further intangible benefits.

ANALYSIS

There are three orders of interactions involved in 'SmartSurfaces' (see Figure 1). On the individual level, students bring their domain-specific skills and knowledge to bear on the course projects. As a crude, stereotypical example Materials Science and Engineering students may have some prior knowledge of programming; Architecture students may have computer-aided drafting skills; Art & Design students may have fabrication skills. The projects require that they pool these and instruct each other in order to succeed. Even when students do not develop sophistication in the application of these skills for themselves they gain an appreciation of what it takes to do them well by observing their peers. It is unlikely that the students that already have skills have applied them to something of the nature of the 'SmartSurfaces' projects. From undertaking an intense project on a cross-disciplinary team the students find out about themselves as learners and gain knowledge about different tactics and methods for acquiring, integrating and using new knowledge and new forms of knowledge. This can be affirmative - confirming for example that the student really does want to be an engineer, or transformative – causing the students to radically rethink their options for employment or graduate school.

At the team level the students must establish values and goals in order to describe exactly the nature, scope, or meaning of an appropriate project – and necessarily make the project function by a deadline. This is achieved primarily through negotiation, both informally through discussion and in written form as the team contract. As the students pitch ideas to one another and defend their opinions and points of view they also make prototypes and subject these to various forms of testing (e.g. aesthetic, functional and behavioral). The contribution of knowledge and values from different disciplines means that there will be debate over what constitutes success, and how it should be evaluated. As the teams iterate and evolve their projects, these values and goals become shared. The teams need to maintain a guiding vision that motivates the general direction of their work but that allows team members to compromise, make concessions and synthesize their points of view. The students must learn to integrate other's points of view and evaluate the statements they make. They need to be willing to reframe the opportunities that emerge and to bring to bear the different insights they have.

At the level of the course, the students are given access to a broad range of tools and resources.[12] The students have the responsibility to decide what is most important and which team members are most appropriate to focus on what is necessary to implement their project as determined by the team. In the process, 'SmartSurfaces' students are encouraged to exploit the triple-unit nature of the course and the endorsement of three professors to help them to overcome perceived and actual discipline-specific barriers to access, subject to the pressures of weekly, public critiques. The combination of the freedom and responsibility of the students defining their own objectives and of having access to facilities and equipment and being trusted with the $3,000 budget to select their own materials constitutes a crucial motivator for the students to invest deeply in their projects.

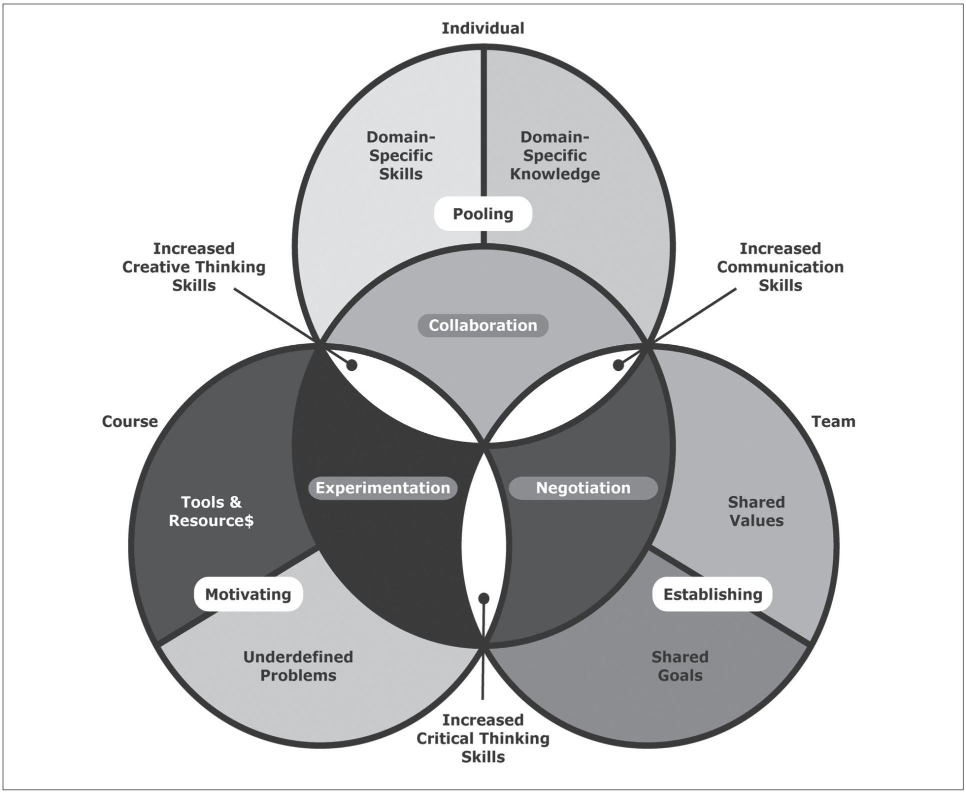

Figure 1: A model of three orders of interactions involved in the 'SmartSurfaces' course.

One of the most interesting aspects of the course is witnessing the students become conscious of the disciplinary preconceptions that they have been trained to have. Many students are surprised to discover that they actually learn more about their own discipline through this course – in their regular courses the fundamental tenets of their discipline remain unquestioned or ignored. Many students have changed their senior theses or their choice of a graduate program because of the experiences they had on this course. The number of superlatives used in the evaluations of the course is striking - these examples are fairly typical:

> "This was by far the best course I have ever taken at the University. The amount of work required for the class is ridiculous, but it is work put in voluntarily because of the passion we have for our projects. I've learned so much from this class, and it will likely affect my career."[13]

> "This class teaches on a level that surpasses the prototypical American education system. What I got out of this class affected me at a core level to the point that it greatly influenced my life goals."[14]

CONCLUSIONS

'SmartSurfaces' brings together faculty and students from different disciplines to tackle real-world problems in a hands-on manner. It develops thinking through making, resulting in personal buy-in and ownership of the learning process by the students. Thus, the students become active learners - they understand the problem's origin, significance and value for themselves because they play a role in defining them, leading to transformational learning experiences for the majority of the students involved. While the initial evaluations of 'SmartSurfaces' have been clearly positive - several important issues became evident, requiring further consideration:

1. The course is very resource intensive. It has involved three faculty, twenty-four students, a specialized non-traditional space, and 24/7 access to equipment. Aside from the obvious financial and human capital burden the current arrangement places on the units, there is the question of whether in future the experience can or should be scaled to greater numbers of students on a regular basis?

2. There is no doubt that due to existing curricular constraints, the group of students that have elected to take 'SmartSurfaces' was highly self-selecting. This raises the question of whether this type of learning experience would extend effectively to a more typical cross-section of our undergraduates?

3. The majority of students that have taken the course were seniors. How might this type of learning experience be realized in the earlier stages of students' careers at University of Michigan?

In closing, it is important to point out that we are not proposing to replace the existing curricula with cross-disciplinary, integrative courses. After all, one cannot be cross-disciplinary without disciplines. It is also important to acknowledge that the authors (and students) elected to do this course. We think success in this type of course is highly unlikely if units impose this type of course on reluctant faculty (or students). The very open-ended nature of such a course is notoriously difficult for most students to assimilate and for a large fraction of the typical faculty to teach. Finally, simply finding a time to meet that accommodates three distinct curricula is a significant challenge in itself. Nevertheless we are continuing to test the framework we have established for this course by moving into new contexts. In Fall 2011 we will work with an incorporated non-profit whose mission is to develop and implement neighborhood stabilization strategies in a Detroit neighborhood near Hamtramck. 15 We will focus on making 'Power House SmartSurfaces' that address the needs of the neighborhood. We are also currently seeking industry partnerships and government agency support as alternative future funding models for 'Nano-functional SmartSurfaces' for Fall 2012.

ENDNOTES

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11. Conversation with Crisca Bierwert, August 16, 2010.

12. Beyond the physical resources of the University, students also have access to an extensive library of resources through a 'SmartSurfaces' online collaboration and learning environment (CTools) as well as the public site for the course. http://www.smartsurfaces.net/

13. Statement from 'SmartSurfaces' student collected by University of Michigan Office of Evaluations & Examinations.

14. Statement from 'SmartSurfaces' student collected by University of Michigan Office of Evaluations & Examinations.

15. Power House Productions (PHP) http://www.powerhouseproject.com/