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Best Practices for Enabling Effective Cross-disciplinary Learning in Interdisciplinary Project Groups*

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FINE392: Technology Art Studio is a unique course developed as a collaboration between Engineering and Fine Arts at the University of Waterloo. Both disciplines require the application of significant creativity and problem solving, and the unique context of this course provides fascinating opportunities for immersive, cross-disciplinary learning, not just of the immediate subject material, but of working methods and approaches. The course provides an opportunity to research the effective facilitation of cross-disciplinary fertilization, both in the course and in the broader context of other interdisciplinary interactions. This paper describes the course learning goals, structure and syllabus, and presents several examples of student work. Through the results of a feedback questionnaire administered to students as well as instructors' reflections on three offerings of the course, we investigate evidence suggestive of student transformative learning and present a number of best practices we have identified.

Keywords: collaboration; interdisciplinary; cross-disciplinary; studio courses; sculpture; engineering; learning transformation

INTRODUCTION

ENGINEERING DESIGN is a practice that requires the ability to reason critically and creatively. Traditionally, design as a discipline was taught only in select programmes within faculties of engineering (e.g. Industrial Design Engineering, Systems Design Engineering). How to teach students to think creatively was all but ignored in traditional curricula, probably due to the difficulty in 'teaching' creative practice with the rigour and strict assessment models that characterise typical engineering programmes. Students, it is generally reasoned, will hone their ability to think creatively through practice. While it is true that creative thinking develops through practice, students must be provided with projects which challenge their current level or mode of creative thinking, in order to develop further.

Thankfully, engineering curricula have in the past decade evolved in this respect, to the current point where nearly every engineering undergraduate programme includes some form of capstone, open-ended group design project. In some cases, the opportunity exists for these projects to take on an 'interdisciplinary' nature, which in the context of most programmes means engineers from different departments collaborating with each other. This is excellent preparation for the type of teamwork that will characterize many engineers' post-graduation work environments.

At the University of Waterloo (UW), we have introduced (in addition to the core capstone design project) a novel elective course, *Technology Art Studio*, which challenges engineering students to think creatively in a context entirely different from the traditional design project. In this course, engineering students collaborate in small groups with sculpture students from Fine Arts, on technology-mediated sculptural works. Both engineering and fine arts require the application of significant creativity and problem solving, and the processes applied by practitioners of each are in fact quite similar [1] despite the apparent disciplinary separation. In fact, the two disciplines were quite close before the industrial revolution and the increasing specialization seen in the technical disciplines. The 13-week course is structured as a one-hour lecture slot and a three-hour studio slot, weekly. The course is co-taught by faculty from Engineering and Fine Arts, with both instructors attending all lectures and studio sessions. We admit an equal number of students from Engineering and Fine Arts, typically seven of each. Engineers have come from the third- or fourth-year (junior or senior) Electrical & Computer (ECE), Mechanical & Mechatronics (MME), and Systems Design Engineering (SYDE) programmes, and artists are in the upper years of the sculpture specialization. For

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purposes of accreditation by the Canadian Engineering Accreditation Board (CEAB), the course counts as a Complementary Studies Elective.

The FINE392 curriculum includes lectures on formal sculptural concepts, collaboration, installation work, user-centered design and technology art history. Three-hour hands-on workshops are given on introduction to sculpture (for engineers only), electricity and electronics (for artists only) and microprocessors (using the PIC 16F84A). With the exception of the first two workshops, students attend all lectures equally. These topics are supplemented each term with presentations from visiting technology artists, visits to local galleries as appropriate and critical discussion of examples of current practice. The course culminates in a three-day public exhibition of student-created work.

There are several different goals for this course. Institutionally, we hope it will form the basis for rapprochement and expanded interaction between Engineering and Fine Arts. We feel there is much to be gained from this dialog and envision greater collaboration at the undergraduate, graduate, and research levels. Pedagogically, the main goal of the course is to expose students in each discipline to the thinking and methods of the other in an innovative learning environment. By collaborating in interdisciplinary groups, we expect that participants will learn to express themselves and their ideas *without* the shared jargon of their disciplines. In seeking ways to explain engineering and artistic concepts within their groups, we hypothesize that students expand their own understanding of the topic. Engineers in the class are exposed to alternative ways of approaching the creative process, as well as alternative motivators for design. Artists learn about technology as a medium, technology art practice, and the potential and limitations of the medium.

Research context

In this section, we briefly review the literature related to interdisciplinary educational experiences for engineering students. We position our research relative to the extensive body of literature on curriculum integration, and establish the framework for analysing evidence of transformative learning from student feedback. The term 'interdisciplinary' is used widely in the educational literature, particularly pertaining to engineering students. One common usage refers to course-based or extracurricular projects within engineering which draw students from different departments. In the Interdisciplinary Design Programme at Texas A&M University, for example, students from different engineering disciplines collaborate on capstone design projects [2, e.g.]. Extra-curricular faculty-wide student team projects such as solar cars, alternative fuel vehicles and autonomous aerial vehicles are further examples. In other cases, engineering students may collaborate with students from other disciplines in mixed courses; for example, on case studies or mock projects around intellectual property and commercialization of technology [3, e.g.].

Here, the adjective interdisciplinary describes activity involving interaction between students of different disciplines. For example, FINE392 is an interdisciplinary course, in which students work in interdisciplinary teams. Cross-disciplinary describes activity that involves 'crossing' disciplines, which is stronger than interacting and includes the notion of movement or transposition of knowledge. For example, students will have interdisciplinary discussions (i.e. between engineers and artists), during which we hope some cross-disciplinary learning will take place (i.e. concepts will cross disciplines and be integrated into the conceptual framework of the other). We must also distinguish between conceptual integration—the successful inclusion of new ideas into students' conceptual models—and curricular integration which entails the combination of different curricula in order to improve different measures of student performance. Unless specifically qualified, the term integration refers to the former.

Recognizing the potential of open-ended interdisciplinary projects to build creativity, several institutions have initiated programmes designed to provide breadth and (usually project-based) curricular integration [4, e.g.]. Some programmes have further demonstrated the benefits of teaching such curricula using the studio model typically applied in the fine arts. In this model, students are given the tools and then encouraged to explore for themselves, with instructors physically present to critique and provide guidance [5, 6, e.g.]

In their comprehensive review of integrated engineering curricula [7], Froyd and Ohland surveyed over 40 papers having keywords related to 'integration', and over 120 works related to curricular integration within fourteen US engineering programmes. One of the major difficulties pointed out by researchers in participating programmes is the difficulty in designing assessment tools to evaluate the effectiveness of integrated curricula since the success measures are often qualitative. In the case of FINE392, we are just learning what we are looking for and have recently begun a study with more formal research instrument design. However, we are not yet reporting complete assessment data related to our learning goals for students, and therefore do not meet the second of three criteria set out in [7] to define 'integrated curricula'. Still, the other two criteria—interdisciplinary faculty collaboration in developing and implementing the curriculum, and students enrolled from different disciplines—are met, so it is worthwhile considering how our work relates to the spectrum of reviewed research.

All of the projects reviewed in [7] concerned freshman or sophomore engineering students either enrolled in core courses from different disciplines or in a single core course combining students from multiple disciplines. The most common combinations were students from different branches of engineering, or from engineering and science. They listed no examples of collaboration between students from engineering and fine arts. The identified goals of curriculum integration that are specific to student learning were:

1) improving disciplinary learning;
2) increasing non-technical skills;
3) improving student retention in engineering;
4) increasing student diversity.

The authors conclude that integrated curricula can improve disciplinary learning and student retention, but that such programmes (as defined and reviewed in their study) are less successful at increasing the non-technical aspects of learning emphasized by new accreditation standards from ABET and other institutions. Integrated curricula can also aid the formation of learning communities as a by-product of the clustering of students from different disciplines [7]. In the case of FINE392, the only real shared goal *vis-à-vis* engineering student learning is that of improving the so-called 'soft skills', and we hypothesize that the interdisciplinary collaboration will have an effect on acquisition of such skills. We do not expect, given the cultural diversity of participants in the course and the lack of other common courses, to foster any ongoing learning communities through the course.

Outside the review by Froyd and Ohland [7], we found a few reports of collaborative courses involving fine arts majors and engineers or computer scientists. In [8], interdisciplinary teams of students from Computer System Engineering and Fine Arts worked together to create a visual performance using the 'Shuriken' autonomous robot. In [9], computer science students worked with students from fine arts to create artistic virtual reality (VR) environments. The authors list as one of the course goals, the study of interdisciplinary group dynamics, and collected data on students' collaborative experiences through a class log. However, the data are not analysed or presented in the paper. In another collaborative course project combining artists and computer scientists, VR software was used to incorporate artist-created digital banners into neighbourhood photographs [10]. In each case, the authors refer to both the challenges and opportunities for personal and professional development afforded by the collaboration across widely different disciplines, hinting at the transformative aspects of the learning experience.

Similarly, we feel the unique setting of FINE392 provides fascinating opportunities for immersive, cross-disciplinary learning, not just of the primary subject material, but of working methods and approaches. There are two key aspects of FINE392 which result in an opportunity for novel research into cross-disciplinary learning: much of the extant literature focuses on teaching specific topics to non-specialists (e.g. art-for-engineers, business-for-engineers, technology-for-artists), as opposed to interdisciplinary student collaboration, and there is little or no research on collaboration between student engineers and artists. Despite this, existing studies on the effectiveness of interdisciplinary collaboration do emphasize the importance of this model [11, e.g.]. By explicitly 'forcing' engineering students to work collaboratively with sculpture students on projects that differ significantly from their usual engineering project, FINE392 sets up an environment conducive to creativity and transformative learning. Specifically, it encourages students to 'think outside of their comfort zone and expertise', to experiment and to 'change their routines and think laterally'. These are three conditions recognized as helping to construct a creative classroom environment [12]. Along with the interdisciplinary collaboration, this environment also helps create the conditions for the paradigm shift/perspective transformations associated with transformative learning. Cranton describes transformative learning as taking place when [13]:

> Through some event, traumatic or ordinary, individuals become aware of holding a limiting or distorted view. If they critically examine this view and are open to alternatives, they may consequently change the way they see things. They have then transformed some part of how they make meaning out of experience.

Based on this description, we see three progressive stages to transformation:

T1 recognition of the limitations of one's pre-existing thought models, followed by
T2 the examination of these models in light of alternatives, potentially leading to
T3 transformation of one's conceptual model.

Thus, we view transformation—which is intimately related to learning transfer, or the ability to apply learning from one setting to another context—in the same way as [14]. That is, as 'a dynamic process rather than a passive end product of a particular set of learning experiences'. In the presentation of student works and analysis of feedback which follows, we will identify indicators that these cognitive events are occurring in the course of students' collaborative projects. For ease of reference, the designations 'T1', 'T2' and 'T3' will be used throughout the article to refer to the above stages of transformation.

STUDENT PROJECTS

We begin this section with descriptions of the projects assigned through the course of the term, and relate the goals of each project to the three identified stages of transformational learning. We then describe four specific projects which were completed by student groups, and comment on them in relation to the transformation spectrum.

Assigned projects

Several projects were assigned through the course of the term: two to three short projects in the first 4–6 weeks and a larger 6–8 week project during the remainder of the term. Table 1 below shows a list of project titles with a brief description of each. Not all projects were assigned in all terms. Most of the projects are done in interdisciplinary groups, with students collaborating on their works during studio time and outside of class time. All projects include a formal group critique, where students present their work for critical assessment by the instructors and feedback from their peers. Works are graded according to a set of criteria made available in advance to the students. The grade depends on the extent to which the project meets the goals of the assignment, its strength outside the context of the course, and formal sculptural aspects. All members of a group are assigned the same grade for the work.

Broadly speaking, the projects are assigned in an order which encourages progression along the spectrum of transformative learning listed earlier, from T1 to T3. For the engineers, the *Book Project* requires that they consider success criteria which they are not used to (e.g. successful use of space, colour, form and materials) and thereby challenges their pre-conceived notion of a successful project (T1). In *Toy Hack*, they are again asked to consider these criteria and must also work within the constraints of the pre-existing interface on whatever toy they have chosen for their piece. The group critiques of *Book Project* and *Toy Hack* provide an opportunity for the engineers to examine their existing views of success in the context of the artists' and instructors' feedback (T2). For those who are more advanced along the transformation spectrum, critiques provide an opportunity to test out their nascent models. By being critiqued and participating in the process of critiquing their fellow students' works, students hear and employ the language of the other discipline.

These initial projects are followed by a small-scale collaborative project (*Freeing The Mind*) and the larger-scale final project. While the final stage of transformation, T3, is more difficult to orchestrate, project expectations grow progressively and

Table 1. Project assignment descriptions

Project Title	Project Description	Specific Goals
Book Project (T1)	Students are provided with a selection of used hardcover books and asked to choose one and create a sculpture using 100% of the material from the book. They may use the book's content as conceptual material for the piece, or make it purely formal. This is a one-week individual project used in 2004 and 2005.	• To introduce engineering students to sculpture. • To help instructors gauge competency levels and conceptual interests among both engineers and artists.
Toy Hack (T1)	Students are asked to chose a toy and subvert it in some way to make a statement or provide an experience for the viewer/user. The piece must include electrical or electronic components. In 2005, assigned as a two-week individual project. Used in 2006 as a three-week group project. Not used in 2004.	• To introduce fine arts students to electronics in a self-directed project context.
Egg Launcher (T1, T2)	Students are asked to choose a major art movement and create a sculptural work made from at least 80% corrugated cardboard, that will launch an egg the furthest. The piece must be conceptually and/or visually executed in the style of the chosen art movement. Two-week group project used in 2006.	• To explore the integration of simultaneous artistic and engineering constraints.
Freeing the Mind (T2, T3)	Students are asked to create an object incorporating electronics, and given the Star Trek "Tricorder" as a model of a fictional device which can be assigned whatever functionality comes to mind. Importance is placed on how the stated functionality informs the physical form and the experience of the user. Assigned in two stages: FTM1 is an individual "paper" assignment (sketches and concept only). FTM1 concepts were used to assign groups, and the project was re-assigned as a three-week group project, FTM2. Used in 2004 & 2005 only.	• To explore the technologies that the class finds motivating. • To assist instructors in assigning groups with similar conceptual interests.
No Holds Barred (T2, T3)	A "paper" assignment (sketches and concept only) in which students are asked to draw inspiration from technological items in our environment, and propose a piece which subverts that commonplace technology into an experience which could be considered art. Implementation issues are not considered, and emphasis is on the form and meaning of the piece and the experience of the viewer in interacting with the piece. Used in 2004 only; assigned in Week 6 as a 1-week individual project.	• To explore the limits of students' creativity when unconstrained by limitations of implementation or current technology. • To help instructors assign groups for the final project (2004 only).
Final Project (T2, T3)	An open-ended assignment to create a technology-mediated sculptural work. Assigned in the last 6–8 weeks of the course, in interdisciplinary groups ranging in size from two to four members.	• To produce work for the final show. • To provide an extended project in order that students develop their collaborations.

Fig. 1. *Aural Ice* (2005) by Natasha Graham, Ryan Grant, Dawn Stafrace.

implicitly require the students to rely on increasing, and increasingly successful, collaboration. We expect that this increased level of collaboration will provide the impetus to complete the spectrum of transformation.

Selected student works

The following works are representative of the magnitude and quality of the project pieces created by students. They were shown during the three-day annual end-of-term exhibition titled *t'art: Technology Art Exhibition*, in the main foyer of the central engineering building on the campus.[1] In general, the success of the final piece mirrored the instructors' perceptions of the success of the collaboration and the level of interdisciplinary interaction within the group.

Aural Ice (2005) by Natasha Graham, Ryan Grant, Dawn Stafrace

Aural Ice (Fig. 1) was a response to the final project assignment, created by a group of two artists and one engineer in 2005. In a quiet secluded space, a block of ice hangs by chains (left) from the ceiling above a glass water-filled bowl (right). As the ice melts, drips falling into the bowl generate soothing ambient notes, creating a calming zen-like experience. The group used a webcam inside the plinth supporting the bowl to detect ripple patterns in the water. A MATLAB[2] script processes the images in real-time and generates a tone which is a function of the spatial location of the drip in the bowl.

This group worked well together, meeting frequently on and off campus outside class time, and the engineer contributed to generating the conceptual ideas for the piece. At least one of the artists underwent significant transformation, as can be seen from these chronological excerpts from her sketchbook which range over a period of six weeks from overt scepticism to fully embracing the idea of technology art.

- And the work . . . is it all lights and sounds? reaction to an action? Are we just feeding the experience machine? Need, need, need. flash. satisfied.
- [One of the students] said that the artists should be artists and the engineers should be engineers. I am uneasy about this statement. True it will be hard to deny either position but if each side doesn't explore the other than why are we all here? (T1, T2)
- While we were doing the electrical parts we all took turns soldering and connecting switches and modifying the answering machines. It was really great. (T2)
- I am impressed that I came up with an idea for a tech project outside of the tech class. It is interesting to realize that this is already playing a part in my regular stream of [consciousness]. I am using the technology that I have learnt in this class to think of things that a few months ago would have never crossed my mind even as possibilities. (T3)

Fix Your Own Damned Breakfast (2006) by Donald Duff-McCracken, Paul Groh

Fix Your Own Damned Breakfast was a collaboration between an artist and engineer for the *Egg Launcher* project in 2006. The piece is shown in Fig. 2, and the artists' statement reads:

> *She stands in 2 dimensions. Or is it three? There is probably more to her than it seems. Or that you have led yourself to believe. Perhaps it is time to fix your own damned breakfast.*

Fig. 2. *Fix Your Own Damned Breakfast* (2006) by Donald Duff-McCracken, Paul Groh

[1] Complete documentation of these and other works can be found online at http://tarsas.uwaterloo.ca/tart

[2] MATrix LABoratory, scientific computation software from The Mathworks, Inc.

For their work, the students chose an image representative of the mid-20th century domestic housewife (Fig. 2). The image is crudely enlarged, revealing the printing dots reminiscent of the Pop Art movement of the 1950s and 1960s. The image is laminated to several layers of corrugated cardboard, resulting in a flat but three-dimensional work. The base, also of laminated cardboard, reinforces the dimensionality. The figure holds a real frying pan, into which the egg is placed. A vintage kitchen timer controls a solenoid to trigger a spring and release the cocked arm, thus launching the egg. The electro-mechanical release mechanism is integrated artistically into the form at the back of the piece.

The integration of technology and artistic material in this work, down to the detail of the vintage timer as a trigger mechanism and the 'wiring' at the back, suggest that the group had a tight and successful collaboration with ongoing communication throughout the project. The engineer's comments demonstrate at least stage T2 transformation:

- Specifically for the egg launcher, [collaboration] meant understanding the art movements that my partner suggested, listening to some of his design theories and then presenting some additional features to his design. In return, [my partner] did the same with my ideas and together we came up with three good designs that we could have used for this project. In the end, we chose the one that would be the most fun to create and best reflected the [integration] of art and technology. (T2)

Post-Critical Zoetrope (2005) by Matt Millard, Rick Nixon

This dynamic piece, shown in Fig. 3, is in homage to Eadweard Muybridge's revolutionary nineteenth-century series of images, The Horse in Motion. It took Muybridge six years to capture the stop-motion images of a horse in full gallop, after being retained by Leland Stanford to confirm that there was a point in a horse's gallop when all four hooves were off the ground. The images are reanimated and played on a laptop computer, which in turn rotates on the end of a boom in a circle reminiscent of a racetrack, 'giving the life back to the original source of observation, the once-living horse and rider'.

Fig. 3. *Post-Critical Zoetrope* (2005), by Matt Millard and Rick Nixon

The artist and engineer who collaborated on this project had a successful partnership which included a lot of back-and-forth across disciplinary boundaries, as is evident from this quote from the artist suggesting at least stage T2 transformation.

- I can assure you that artists have an exalted view of themselves, and it is both reassuring and daunting to see that high opinion questioned. I dug my heels in more than once over an aesthetic concern. Contrary to what I expected, my engineer partner was very committed to the aesthetic. Conversely, I found myself arguing for certain mechanical decisions that drew from sources unavailable to the engineers.

Symbiosis (2006) by Avrum Hollinger, Paul Groh, Stephen Moore, Katie Tyrrell

Symbiosis (Fig. 4), was a final project piece created by two engineers and two artists in 2006. The work is a comment on society's reliance on increasingly complex technological advances. It asks the viewer to consider how it is that the brainless jellyfish can survive 450 million years without technology, and why humans seem to require it.

The scale of this work is such that viewers can walk in and among the 30 or so jellyfish of various sizes which hang suspended from a 'sea surface'. The larger jellyfish contain LEDs and small speakers which make periodic noises, as if the creatures were trying to communicate. A motor with an excentric mass is fixed to the hidden side of the hanging structure, and is intended to shake the hanging jellyfish to simulate ocean wave action.

It appeared from the instructors' perspectives that communication between the artists and engineers was ineffectual. Although there was evidence of initial brainstorming as a group, and the artists worked as a pair, it seemed that tasks were divided very clearly along disciplinary lines and carried out independently. This was true even between the engineers, who were from different engineering disciplines. This disconnect prevented effective

Fig. 4. *Symbiosis* (2006) by Avrum Hollinger, Paul Groh, Stephen Moore, Katie Tyrrell.

project and integration planning, and compromised the final product. When the final material selection and physical design for the jellyfish took much longer than the group expected, the effect of the delay was exacerbated by the lack of communication and planning.

The final product was quite successful from the formal perspectives of scale, use of space, and choice of materials. In the presence of the work, however, the technology plays an ancillary rather than enabling, role. The piece would have been entirely successful as a sculpture without the technology.

In summary, the three first examples showed work from interdisciplinary groups that worked well together, were entirely open to interdisciplinary discussion and debate, and had positive collaborative experiences. This was reflected in the level of integration of the technology and artistic concept: none of the sculptures are as compelling without the technology. The final sample work described was not as successful as a technology-enabled sculpture. Over all the projects produced in the course to date, our general observation has been that groups which had difficulties creating strong collaboration produced work which was more disjointed. Perhaps not surprisingly, it appears that beyond improving the final work, successful interdisciplinary collaboration also increases the probability of students achieving a higher stage of transformation.

STUDENT FEEDBACK

After the close of the course in 2004 and 2005, the instructors distributed by e-mail an informally constructed guided-question survey (see Appendix). Students were asked to comment on course content, workload, group assignments, projects and outcomes. The main goal was to gather comments regarding course content and presentation, with a view to incorporating suggestions for change into future course offerings. Of the 28 students who were sent the survey, seven (25%) responded (four engineers and three artists). Overall, students who responded indicated that the course had a good balance between theory and practice, and had met or exceeded their expectations. They unanimously rated the workload as high or very high, but also unanimously said not to remove anything. While there were a few specific suggestions regarding content and delivery, what surprised us was the extent to which their answers to the open-ended questions suggested that many of them had experienced some degree of transformative learning during the course.

In designing FINE392, we hypothesized that the interdisciplinary collaboration required to produce a successful sculpture would provide the impetus for students to become aware of limitations of their existing world view (T1). Classroom discussions, project critiques and group work sessions certainly exposed engineers to alternative viewpoints (T2) and, if open to change, the opportunity to alter their conceptual models (T3). Thus, the course sets up conditions favourable to transformative learning. While the surveys were not designed to explore this aspect of student learning, responses provided evidence that students were moving, to varying degrees, along a continuum of transformation.

For the purpose of analysis, individual artists were identified as A1, A2, and A3; engineers, as E1-E4. Their responses were then analysed for statements indicating the various stages of transformation:

T1: statements recognizing disciplinary differences;
T2: statements referring to interdisciplinary discussions, or the cross-over of information from one disciplinary partner to the other;
T3: statements suggestive of the integration of other-disciplinary concepts or views into the respondent's practice or thinking.

Table 2 shows the results of this analysis for those five students whose survey responses suggested some level of transformation (responses from E3 and E4 did not). Given the nature of the survey and the limited response, it would be imprudent to attempt to draw specific conclusions from the results of Table 2. Nonetheless, a few general observations about some of the responses are noteworthy. Most of the students whose responses suggest they achieved some stage of transformation also made comments relating to the previous stages, supporting the model of progression from T1 through T3 required for transformation. The exception is A1, whose comments didn't include a specific reference to disciplinary differences. Aside from the survey design, this could be attributed to the fact that this particular artist had thought about technology art before and has an adult son who is a computer programmer. She would therefore already have been very much aware of disciplinary differences and have come into the course already having achieved stage T1.

Response A3.3 is also noteworthy. While he talks about integrating the possibility of tech-based work into his repertoire, the artist also gets to the heart of one of the goals of the course. We are not trying to make engineers out of artists, or vice-versa, but trying to open students' minds to the possibilities and working methods of the other discipline. In this case, the artist's response also suggests a transformation from being uncomfortable with technology and collaboration, to understanding the potential and being open to collaboration with non-artists.

Further evidence of the transformative impact on students can be inferred from the path that some take after completing the course. On graduation in 2004, one engineer registered in a qualifying year for the University of Waterloo's MFA programme. Another went on to study theatre at Dalhousie University, claiming that taking FINE392 had given him the incentive to take a risk. An engineering graduate of 2005 is attending NYU's Interactive

Table 2. Survey responses indicating various levels of transformation

ID	Response
A1	1. "I realize now what type of art I will concentrate on in the future. I learned so much in this course, it was really exciting." (T3)
	2. "I am interested in making more tech artwork as soon as I can increase my technical knowledge. I am researching ideas now." (T2, T3)
A2	1. "In my experience, [courses which ostensibly create linkages and understandings between disciplines] have not been able to alter the disciplinary lens through which one normally operates. This was not the case with [this] class." (T1)
	2. "The workshop aspect and the artist/engineer pairing forced everyone to confront those [disciplinary] stereotypes and work through them." (T2)
	3. "I always felt suspicious about tech oriented art: Was it too gimmicky? Doesn't it always break down? Is it too big a pain to access? . . . In the end, I see a whole world of possibilities, and the tech component is a vast archive to research and deploy." (T3)
A3	1. "I found that working with someone outside my discipline really made my training visible to myself. . . . We worked through, and learned through, the strengths of our divergent approaches." (T1)
	2. "In fact a real highlight for me in the course was learning about [my partner's] education and what engineering is generally about. As much as we talked about our projects, we equally were very interested in each other's training and how that knowledge might be applied to our own practices." (T2)
	3. "This course has greatly broadened my knowledge of engineering, contemporary art practices, and has opened me to wider possibilities in my own work. It is akin to learning another mode of communication. . . . I am now more comfortable with the idea of having an artistic idea that might have some elements that would have to be contracted out or collaborated with if they exceed my specific skills." (T3)
E1	1. "It seems there is (often) a fundamental difference in the way an artist's mind works and in the way an engineer's mind works (analysis vs form, understanding vs. expression, etc)" (T1)
	2. "It's difficult forcing the engineers to really think about the meaning behind the projects being created." (T1)
	3. "it often seems that when a piece is dead-ended, artistically, the engineer can provide a sounding-board for artistic inspiration, or if the artist is having difficulty with the construction of the piece, the engineer can help" (T2)
	4. "Something very important that I gained from this class, and that I will take with me wherever I go, is a broader sense of the capabilities and the possibilities for the engineering skills I have. . . . Never before have I been challenged, as I was in this course, to really think about the meaning of what I was making; not only IF or HOW I could build it, but whether I should and whether it would be a good final product. Not just good to sell or good to buy, but good just good. And this is something fundamental; something I wish I'd realized much earlier in my academic and career path. . . . There remains so much unexplored about the positive or culturally enriching capabilities [engineering] may have." (T3)
E2	1. "I imagine that the artists are more used to engaging in the creative process on a day to day basis, but I think it was tougher for the engineers. . . . Again, I expect the artists benefit the most from [the lectures on installation, choice of materials, artistic form], because they can combine what they learn in all their courses in their work." (T1)

Telecommunications Programme (ITP) in the Tisch School of the Arts. None had considered anything other than a career as an engineer before taking FINE392.

As we have mentioned, the results in Table 2 were somewhat unanticipated, inasmuch as the study was not designed to explore the transformative aspect of the students' experience in the course. They are also inconclusive, as we know from personal interaction that the engineer identified as E4 did in fact experience some level of transformation during the course. This has motivated the design of a more rigorous study, in order to better understand learning transformations in a cross-disciplinary setting of this nature.

INSTRUCTOR REFLECTION

Our general observations of course outcomes are that the 2006 offering differed significantly from the two previous offerings. There appeared to be less harmony among the groups, and less commitment among both engineers and artists to the course. This was reflected to a significant degree in the success of the final projects produced by the 2006 groups. Before we describe the outcomes of this reflective process, we explain what we perceive to be the substantive differences over the three offerings of the course: the assignments which were used, the makeup of the class and the methods used to assign students to groups for group projects. A timeline of the assignments in each of the years is shown in Fig. 5; refer to Table 1 for descriptions.

Differences between past course offerings

The 2004 offering had 13 students in it: six artists (one 3rd year, five 4th year), four ECE (one 3rd year, three 4th year), two SYDE (one 3rd year, one 4th year), and one ME (2nd year). After the first individual *Book Project*, the proposals from *Freeing the Mind* were used to assign interdisciplinary pairs for the implementation

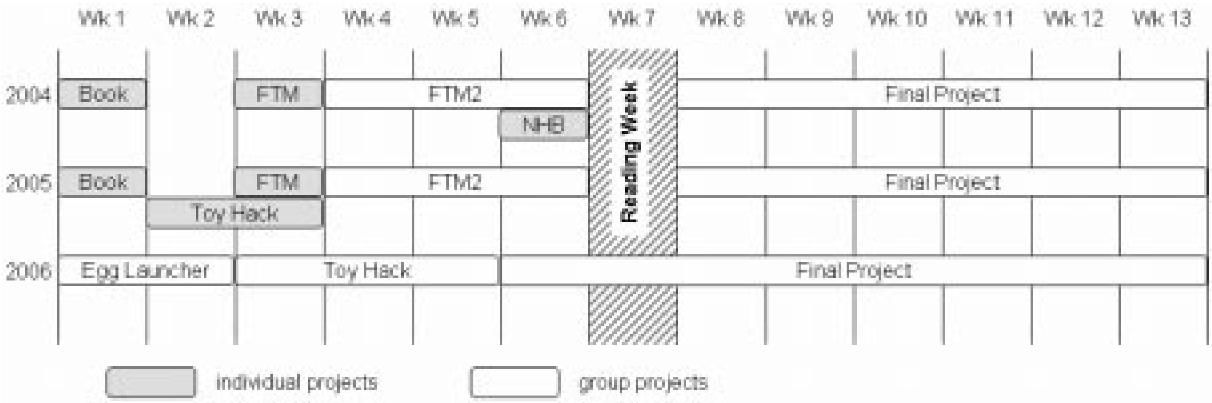

Fig. 5. Timeline of projects assigned in each offering of FINE392.

portion of that project (FTM2). The *No Holds Barred* proposals were discussed in class and students were asked to form themselves into groups for the final project.

The 2005 offering had 15 students in it: eight artists (one 3rd year, three 4th year, four grad), one ECE (4th year), five SYDE (three 3rd year, two 4th year), and one student registered in Independent Studies (Faculty of Arts). After the first individual *Book Project* & *Toy Hack* assignments, the proposals from *Freeing the Mind* were used to assign interdisciplinary two- and three-person groups for the implementation portion of that project (FTM2). These groups were kept for the final project.

The 2006 offering had 14 students in it: seven artists (three 3rd year, three 4th year, one grad), one ECE (4th year), two SYDE (3rd year), and four ME (two 3rd year, two 4th year). Students were randomly assigned in interdisciplinary pairs during the first lecture and immediately assigned *Egg Launcher* as a group project. Pairs were reassigned for *Toy Hack*, to allow students to collaborate with a different partner. For the final project, students were asked to suggest their preferred partners and group size. Instructors attempted to accommodate while ensuring each group contained at least one artist and engineer, and maximizing exposure to new partners. This resulted in two groups of four, and two groups of three.

Instructors' reflections on implementation

Individual assignments: in 2004 and 2005, students started the term with individual assignments. This was changed in 2006 with the intent of allowing students to work with more partners before choosing groups for their final projects. In retrospect, the individual assignments may have played an important role in subsequent group dynamics. The *Book Project* allows the engineers to experiment with sculpture themselves, while at the same time reinforcing the time commitment required for a successful sculptural piece in both reflection and implementation (i.e. making good art is not easy). The individual version of *Toy Hack* assigned in 2005 created the equivalent opportunity for artists: they were allowed to experiment on their own with basic electronics in the context of a simple sculpture. As a result, the dynamic in later group projects appeared to be generally more fluid in 2004 and 2005, compared to 2006, with engineers contributing more to creative aspects and artists participating more in the technical implementation aspects. The result was greater group cohesion, a greater sense of collective ownership of projects, and better projects overall.

Selection of groups: in 2004, we approached group assignment with the goal of matching students with similar conceptual and aesthetic interests. This approach of instructor-selected groups based on common interests is consistent with literature on working with teams, particularly [15]. The *Book Project* was used to evaluate individual students' capabilities and aesthetic tendencies. The intent was to use the individual proposals for *Freeing the Mind* to pair students with complementary interests. This was not as obvious as we had anticipated, except in a few cases where similar proposals were received. The result was that pairs were formed somewhat randomly, and were asked to combine their *Freeing the Mind* proposals for the implementation phase (FTM2). This process was difficult in some groups. In some cases, neither partner wanted to compromise; in others, partners were unwilling to challenge each others' ideas. It is expected that this latter phenomenon would become less of an issue if partners had longer to work together and get to know one another. A few students indicated their desire to change partners for the final project, and we decided to allow students to choose their final project groups, with the option of staying together. Again, this proved problematic when students were reluctant to disappoint their partners by saying they wanted to change. One student likened it to trying to end a relationship without hurting the partner. In the end, we took the students out to the local pub and didn't let them leave until the groups were finalized.

In 2005, the two individual projects at the beginning and a class field trip to visit Toronto galleries provided ample opportunity for students to assess each other. We considered asking students to choose their own groups, but based on the experience with the final project in 2004, decided against it. We used the same mechanism as in 2004 to create the initial groups, based on our assessment of the initial projects and the *Freeing the Mind* proposals. In 2005, however, we decided to keep students in the same groups for the final project. The quality of the final projects was quite high, and we got little negative feedback from groups on their collaborations.

In 2006, we approached group assignment with the philosophy that the collaborative experience would be richer for having worked with as many different partners as possible. Individual assignments were dropped, and each student worked with three to four different students from the other discipline over the course of the term. As might be expected, this approach meant that final group partners had for the most part not worked together before. This was reflected in the apparent level of comfort and commitment within the groups, and may be one reason that final project concepts seemed to take longer to finalise in 2006 and resulted in less finished work by the end of term.

As a general conclusion, it would appear that depth of experience with consistent partners provides for a more successful collaborative experience than breadth of experience with different partners. While it is difficult to discount the effects of varying personality and individual commitment, it would appear that maintaining group assignments across projects leads to a more complete experience and allows for more significant interaction of the type the course is designed to provide. This is consistent with findings from Felder, that groups should not be reformed too often [16].

Shared Space: in 2004 and 2005, students for the most part kept their projects in the studios of the fourth-year or graduate artist in the group. This gave them a common space, accessible 24 hours/day, in which the engineers and artists could meet to work on the project. In 2006, half of the artists were in third year, compared with just one each in 2004 and 2005. Without dedicated individual studio space, this meant it was not as easy to house projects on campus. As a result, most were housed elsewhere, making it more difficult for group members to work together and reducing interaction between groups. The importance of shared space in the success of the studio course is well documented [6, e.g.], and this may help to explain the observations regarding group dynamics and commitment. Indeed, one of the 2006 final projects was too large to conveniently house off-campus, and was instead located in a general-purpose studio on campus where the group spent time interacting with one another and with other artists using the space. This ended up being one of the more successful collaborations.

As one engineer reflected, 'I think the biggest lesson [from the first collaborative assignment] is that you really have to meet your partner in person to discuss things rather than try and use e-mail. There are too many ideas and emotions that come out of creative discussions that cannot all be captured in text. Similarly, in the sculpture critique this past week, I saw how important it is to get input from as many people as possible to make the artwork better.' Having a shared workshop space facilitates this critical personal interaction.

Group working models: the stated pedagogical goals of the course assume a committed engagement on the part of students from both disciplines in the creation and execution of their pieces, particularly the final project. That is, if the students are to learn working methods from one another, and benefit from having to explain concepts to their non-specialist peers, they need to be working as a group. We have identified two *de facto* working models for the role of the engineer within the group: engineer-as-consultant, and engineer-as-partner. In the former model, the artist is responsible for the vision and creation of the piece, and provides the engineer with what amounts to a functional specification. The engineer's job is to design a 'solution' for the artist which will enable the piece. The latter model arises when the engineer is implicated in the creative design of the piece in addition to the technical design. Neither model precludes cross-disciplinary learning assuming there is frequent and effective communication between partners. However, the model of engineer-as-partner allows for greater integration of cross-disciplinary concepts, since the engineer will be (at least conceptually) applying the methods and ideas of the sculptor, rather than simply observing them. We have found that engineering students can learn a lot that is directly applicable to their practice from their artist partners, particularly in areas such as brainstorming, group critique/review, materials and fabrication. This transfer appears to be more effective in the engineer-as-partner model.

It should be noted that many engineers engage in technology art collaborations precisely for the engineering challenge of 'bringing to life' an artist's ideas. They may have little desire to contribute creatively, and are more comfortable in the role of engineer-as-consultant. This is entirely in keeping with the history of technology art practice going back to pioneering Bell Labs engineer Billy Klüver [17] and his contemporaries in Experiments in Art and Technology. There is no argument that this model cannot produce fantastic artistic work, but the additional pedagogical goals of the course direct us to favour the second model for the increased opportunity it provides for interaction and transformation.

Another subtle difference between the models has to do with how projects are perceived, assessed and archived in the two disciplines. University engineering projects are generally assessed much more heavily on the process than the final product. The aesthetic appearance of a prototype is not important. If the prototype doesn't function fully, the emphasis is on the student's ability to explain the issues and how to remedy them in (often hypothetical) subsequent design phases. The lifespan of a project is generally no longer than the course itself, particularly if the prototype was not entirely functional. In contrast, the emphasis in sculpture is on how well the piece functions as a work of art, both technically (from both arts and engineering standpoints) and aesthetically. Particularly for upper-year arts students, the works they create with their partners in FINE392 become important additions to their artistic portfolio. Several of the works created in the course have gone on to show in galleries and exhibitions outside the context of the university. Thus, the commitment of the engineering partner to the projects is of significant importance to the artists and their career. Our experience has been that given the timelines, the engineer-as-partner model is much more successful in this regard. The short timelines do not permit most of the large projects to reach a level of robustness and documentation that would allow the engineering partner to simply turn it over to the artist at the close of the course.

There are several steps instructors can take to promote the adoption of one model over the other: by screening during selection of students to admit to the course, by explicitly describing early in the course the two models and their nuances, and by reinforcing the fact that the students will experience the most effective learning if they are able to adopt the engineer-as-partner model.

BEST PRACTICES

In this section, we record and generalize some of the best practices that we have identified as a result of our analysis of the previous three offerings of the course, particularly as they relate to the interdisciplinary interaction. Many of these are already established practices among good instructors within their disciplines, but take on increased importance and entail more planning and preparation in the interdisciplinary context. It is our hope that should others develop similar courses with project group members drawn from vastly different academic backgrounds and cultures, they may benefit from our experience thus far.

Shared space: **acquiring this is worth expending considerable effort on.** Its importance to the success of project work is well documented [6, e.g.]. The tools and resources to which groups would need access should ideally be in close proximity to this space, including the instructors' offices. This takes on even greater importance when group members come from diverse disciplinary and cultural backgrounds and have little opportunity to interact outside the context of the course. We have seen that without such a shared space, students are more prone to work individually and the full potential of interdisciplinary interaction is not achieved. The challenge in securing and equipping such a space is not trivial: in cross-faculty courses such as FINE392, the physical space and resources invariably 'belong' to one or the other faculties, which brings up inevitable resource questions. Many institutions, while encouraging interdisciplinary work in theory, present significant administrative barriers due to the decentralised nature of the university. We have found this to be particularly true when students come from entirely different faculties, and this observation is consistent with reports from the research reviewed in [7]. We believe, however, that the extent of the interaction within and between groups has proved to be a key factor in achieving the objective of cross-disciplinary learning.

Public showcase: **as one of the defining characteristics of FINE392, we showcase very publicly the students' works at the end of the term.** This public exhibition gives the students something concrete to motivate, galvanise and focus their efforts on over the course of the term. It also forces the students to bring the projects to a point where they are at least fit for three days of public display. One recurring comment from the engineering students is that this is the first time they felt that any of their projects has absolutely had to work by a specific date in the term. Not the least because of this, the final exhibition imposes an increased workload on all involved. While student feedback on the surveys acknowledges the heavy workload in the course, they unanimously reject the suggestion that the workload be lightened. A further benefit of the public showcase is the potential for raising public and institutional awareness around the collaboration.

Stakeholders' expectations: **particularly in the interdisciplinary environment, it is important that everyone understand the expectations that others bring to the course and to the projects.** For example, in FINE392, particularly for the upper-year artists, the pieces they execute during the course will become important additions to their artistic portfolio. Many will want to show the pieces again if given the opportunity; several of them from FINE392 have in fact gone on to show in other venues. It is important that collaborators on a project be committed to at least ensuring that it can be reprised by others who are interested. This is a case where the difference in disciplinary culture may lead to significant misunderstanding and ill feelings if there is one person with required expertise and that person is not willing or able to teach others or remain with the project.

Enabling cross-disciplinary learning: **cross-disciplinary learning appears most effective when student groupings remain consistent from assignment to assignment.** Students with shared disciplinary background may quickly establish relationships in which they learn from each other, benefiting from a common prior learning experience and the shared language of their discipline. In contrast, we observe that peer-driven cross-disciplinary learning is not as efficient: students must first learn what they have in common, and establish compatible working methods and effective communication.

It is important that instructors inform the students early on that the more they put into the group, the more they will get out of the course, and emphasise the importance of shared time and space. Since the real potential for cross-disciplinary learning comes from interaction within the project groups, and the majority of this interaction happens outside the classroom, students need to buy into the benefits of collaboration and interaction and assume some responsibility for its success. Early team-building activities can help encourage cohesion, but it may also be a good idea to provide comments from past students on what worked and what didn't.

Group size: **group size should be restricted to two to three students**, if the goals of the course include encouraging cross-disciplinary exchange of working methods and cultures. Without strong project management, organisational issues dominate in groups of four or larger and introduce inefficiencies which smaller groups don't face to the same extent. This is particularly true with the short timelines typically associated with a one-term course. The time pressures can also cause the group to divide along disciplinary lines and work individually on individual aspects of the project. Apart from precluding any significant cross-disciplinary learning experience, without a clear integration strategy the end result is likely to fall short of the group's expectations.

There is a further argument for choosing group sizes of two rather than three to avoid the creation of an 'us versus you' environment, although this depends to a great extent on the individual personalities involved. We have had groups of two engineers and one artist where this became an issue, and other groups of three which worked very well.

While research on team assignment in engineering courses suggests group sizes of three to seven [15, 16, e.g.], we feel that the disciplinary differences inherent in the groups would exacerbate problems associated with larger groups, and that this would outweigh the benefits. Some of these problems are [18]: difficulty arranging common meeting times, understanding each other and reaching consensus, longer time to develop a trusting/working relationship, lack of team dialogue resulting in sacrificed collaboration.

Acclimatization: **include early in the course opportunities for individual students from each discipline to experiment with work in the other.** We feel that this has been critical to creating effective groups for cross-disciplinary learning. In FINE392, these opportunities take the form of the *Book Project* and the *Toy Hack Project.* Although *Toy Hack* was run as a group project in 2006, we will likely revert back to the 2005 model in the future. These individual exercises give students from each discipline the opportunity to practice the other and be critiqued on the result. This is important in establishing an initial set of shared experiences as well as forcing the students to begin to speak with the language of their other-disciplinary peers, and appears to greatly facilitate future communication within the groups. Individual projects where students work in the other discipline are a key enabler of the initial stages of transformation (T1, T2).

SUMMARY

In this paper, we describe a unique interdisciplinary course developed at the University of Waterloo, *FINE392: Technology Art Studio*. The collaboration between engineering and sculpture students in the context of the course projects provides opportunities for transformative learning. Evidence from the three annual offerings to date (2004–2006) suggests that engineering and fine arts students working together become adept at integrating their respective knowledge backgrounds to produce unique sculptural art forms. Generally, we observe that the quality of work improves from project to project, as long as the partners continue to work together, suggesting that this knowledge integration is related to interaction between partners. Further, we observe that strong cross-disciplinary interests develop over the span of the course and, in the case of some students, become integrated into their future study plans.

Preliminary analysis of student responses to an informal post-course survey suggests that students are undergoing various stages of transformative learning during the course. Based on these preliminary results, a more detailed study of the transformative processes at work within the interdisciplinary groups has been designed and is currently underway. We hope this follow-on study, involving student journals, in-class observation and instructor reflection will shed light on the transformative processes *in situ* as students work in collaborative pairs. Our primary research objective is to articulate learning experiences that signal occurrences of transformative learning. A secondary objective is to derive concrete teaching and learning practices that both support and deepen the transformative learning experience. The pilot of this study ran during the Winter 2006 offering of the course and is ongoing. Some preliminary results are reported in [19].

The main goal of this paper is to present what we consider to be several 'best practices' for the design of similar courses, which draw students from disciplines with widely different disciplinary cultures and languages with a goal of fostering cross-disciplinary, potentially transformative learning. These suggestions are: to provide an opportunity for students from each discipline to 'try out' the other individually, to create small groups and keep them together from project to project, to provide a public showcase for students' work, to provide shared space, to emphasize the importance of shared time and working together and to make clear early on the different expectations that students from different backgrounds bring to the course and projects.

We believe that this and similar courses provide an important experience for students, as well as an excellent opportunity to study the mechanisms of effective cross-disciplinary learning, and hope that our lessons will be of benefit to others designing similar learning experiences.

Appendix: Student feedback questionnaire

Topic Area	Question Number
Content	Q1. Did you feel the content of the course was well weighted between theory and practice?
	Q2. Were there components of the course you would have liked to emphasize more (lectures/studio/discussion/slides/workshops)? Why?
	Q3. Were there specific lectures/workshops that you found particularly useful or less useful, and why?
Workload	Q4. How did you feel about the workload in the course, relative to other studio/project courses?
	Q5. How did you feel about the workload in the course, relative to your own expectations?
	Q6. If you feel the workload was too heavy, do you have suggestions of where to lighten it?
Discussions	Q7. Several factors contributed to discussion time being fairly limited. Do you have any suggestions of how to modify things to encourage more interactive discussion (e.g., room changes, more interactive critiques, more social events, etc.)?
Groups	Q8. For the *Freeing The Mind* project you were assigned partners; for the final project you were given the opportunity to change groups. Do you have any specific suggestions about how groups should be formed, their size, and how we might better facilitate students forming their own groups?
Projects	Q9. What did you think of the level of the projects in the course?
	Q10. Where there too many assignments?
Exhibition	Q11. The timing of the final show was a bit awkward relative to exams; would it have been better for you if the show was earlier (which would conflict with more end-of-term due dates) or later (which would tie you up past exams and mean a smaller audience for the show)?
	Q12. There is some interest in moving the show to the back gallery in ECH or to the Artery. What do you think of this idea?
	Q13. Do you have any thoughts on how we could ensure the pieces are "completed" further in advance, to allow for more time to test them and potentially develop them more? Should we enforce a final crit one week before the show (considering the timing with other courses in the term)?
Outcome	Q14. Did the course miss/meet/exceed your expectations? In what ways?
	Q15. In what ways do you think the course will affect you in the longer term?
	Q16. What are the 2–3 most important things you learned in the course?
Future	Q17. What suggestions do you have for the ways in which we might grow this course in the future? E.g., a formal graduate program in tech art, an undergraduate program, research partnerships, community partnerships (e.g., with CAFKA), etc. Be as detailed as you like.
Overall	Q18. Feel free to provide us with any other comments you may have on any aspect of the course content or teaching. Thank you for completing this important survey.

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