AC 2011-2614: UNPACKING THE INTERDISCIPLINARY MIND: IMPLICATIONS FOR TEACHING AND LEARNING

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Unpacking the interdisciplinary mind: Implications for teaching and learning

The challenge

As 21st century science and engineering assault disciplinary boundaries towards addressing problems in healthcare, the environment and energy, many engineering departments are seeking ways to make the curriculum and the classroom more interdisciplinary. Areas as diverse as drug delivery systems, green waste treatment plants, and skin injury treatments are all instances where chemical engineering principles have been applied to pressing problems beyond the purvey of traditional chemical engineering. However, while many faculty readily embrace inter and multi-disciplinary research programs, replicating boundary crossing in the classroom remains challenging, if not contentious. Often, faculty educated within single engineering sub-specialties are not convinced that interdisciplinary approaches are appropriate to the undergraduate level. Graduate school, they contend, is where students can extend and expand their disciplinary horizons. Undergraduate education is for solidifying the fundamentals. Thus, most courses and faculty rely heavily on slow-to-change textbooks that drill the fundamentals while sustaining mono-disciplinary approaches to engineering education. Further, the oft-cited need to “cover” a certain amount of material serves as another major deterrent. This call for coverage is dictated both by the textbooks and by the curricular needs of the follow-on courses. However, the rarely cited issue with coverage is that it is not synonymous with learning; in fact, some might argue that coverage is the enemy of deep conceptual understanding, the desired kind necessary for retention and future application. But undoubtedly, the biggest hurdle to making engineering classrooms more interdisciplinary is the paucity of models for doing this effectively and the numerous questions that need to be addressed in the design of interdisciplinary learning environments. When do you start----early or late? What form should the classroom take? Does interdisciplinary learning need new pedagogies, new learning spaces that defy the large lecture hall, in short, new class configurations? What kinds of measurement can actually get at interdisciplinary reasoning and problem solving? How do you help faculty get comfortable with the idea that students should be given a window on current science and engineering, not just the fossilized versions found in textbooks?

Investigating interdisciplinary cognition and learning at the frontiers of science and engineering

This paper reports on an extended educational experiment that seeks to address these questions in the context of biomedical engineering education. Nevertheless, it has significant implications for the design of interdisciplinary learning in any engineering context because for us *interdisciplinary* connotes a situation where more than one discipline is brought to bear in problem solving. More directly, we want to understand how the reasoning and problem solving practices from engineering and the biosciences are knitted together, accommodated and leveraged in real world problem solving and how we prepare students for this. The paper has three sections that chronicle episodes in an eight-year investigation of interdisciplinary learning both in engineering research laboratories and in an introductory biomedical engineering course.

We begin by briefly reporting on a six-year study of the cognitive and learning practices in two truly interdisciplinary communities and the design principles for classrooms that we extracted from these studies. Then the design and development of the classroom context and content are discussed as they relate to the design principles. Finally the forms of assessment used in this environment are presented.

Our work is based on what we refer to as a *translational* model of design and development for innovation in undergraduate education. Such an approach entails investigating complex in-the-world contexts *(in vivo* sites) to illuminate the ecological features that support learning and then translating study findings into design principles [1,2] for classrooms *(in vitro* sites). We are not the first to look at expert practice outside the classroom for inspiration and replication in educational settings. In response to the AAAS Benchmarks for Science Literacy[3], science and engineering educators (See Linsenmeier et al.[4] and Flora and Cooper [5]) have also used inquiry practices found among scientists to guide the development of inquiry approaches in classrooms. In classrooms guided by this work, students practice answering questions, often of their choosing, designing and conducting experiments, which contrast with traditional instructional labs where students adhere to prescribed procedures to arrive at predetermined results. It has been demonstrated that such inquiry-driven approaches can improve students' abilities to design experiments and analyze data, can propagate conceptual knowledge, and enhance interest in subject matter.

More generally, novice-expert studies, prevalent in the learning and cognitive sciences, investigate experts' reasoning and problem solving practices as contrasted with those of novices to both identify learner misconceptions and to identify developmental learning pathways towards thinking like an expert. Studies of expert physicists solving problems contrasted to those of novices [6,7] have been important in the development of the Force Concept Inventory and in physics curricular reform. While our translational approach is complementary to this work, it differs in addressing the learning processes not in the laboratory where expert-novice work is conducted but rather in sites of authentic work activity. Embracing theories of situated learning [8], we contend that while the ''what'' of instruction is important, the ''where and how'' are equally significant in the design of effective learning environments. In numerous studies, cognition has been shown to be profoundly impacted by context [9]. In our translational approach, we seek to illuminate both the cognitive practices of interdisciplinary experts and how features of the environment afford and scaffold the possibilities for learning; we look for *ecological features* that are conducive to documented positive learning experiences and then try to replicate those features in engineering classrooms.

Our research addressed the more cognitive issue of interdisciplinary integration across engineering and science, integration essential to innovation in biomedical engineering but also in many other engineering endeavors, including chemical engineering. From more than 148 interviews with members of two BME research labs, one focused on engineering vascular tissue and the other on understanding the neurological basis for learning, sustained observation of lab work over a three-year period, attendance at lab meetings, PhD proposals and defenses, mentoring meetings, and laboratory tours for visitors, we distilled five principles used to inform the design of new models for interdisciplinary learning activities and classrooms [10]. In this paper, we choose to focus on the three that are most immediately relevant to the class we will discuss. Some may question whether these principles are generalizable to all interdisciplinary research settings; we do not dispute that each PI has a certain style and way of working that profoundly influences how work and learning are accomplished in the lab. Nevertheless, the fact that we found the same principles at work in two very different lab settings—tissue engineering and neuro-engineering—suggests that the nature of the work itself, discovery and innovation in interdisciplinary engineering, demands a certain work/ learning configuration. These principles represent the social–cultural–cognitive mechanisms that make it possible for undergraduates and new PhDs to find a foothold and then flourish in these rich, complex learning factories. Our efforts to replicate the technology and knowledge rich features of a research laboratory in an undergraduate classroom may seem untenable to some, but we contend that open-ended, ill-constrained, failure-imbued learning experiences truly offer a glimpse of the real work done in advanced science and engineering professional environments. Moreover, the greater number of engineering students going into industry can also benefit from this kind of learning experience because real-world problems and work contexts are not constrained like textbook assignments or lecture halls. Real world problems are messy, require collaboration and often involve moderate failure from which rebound is necessary, much like a research lab. Interdisciplinary reasoning and problem-solving is so complex and challenging that undergraduates need to can only develop the requisite habits of the mind over four years, not just one time in the capstone design course.

Design principles for the development of interdisciplinary courses

Illuminating laboratory learning dimensions led us to hypothesize that a certain kind of problem-based learning (PBL) environment might serve as a vehicle for transference[11]. Our translational work over the last five years has sought to modify more traditional PBL classes to support the development of model-based reasoning, a hallmark of engineering problem solving. In a model-based approach, models are created, manipulated, evaluated, and adapted so as to infer, understand and reason about a target phenomena or a target system. Model-based problem solving is incremental and involves bootstrapping; for instance, a qualitative model in the form of a sketch or diagram might be then translated into a mathematical model or constructed as a physical model. With some kinds of dynamic models, simulation that produces new model states is involved in these cycles; evaluation often involves experimentation. Philosophical accounts developed from the study of scientific practices argue that *model-based problem-solving and reasoning* practices are the signature of much research in the sciences, both in discovery and application [12,13].

We refer to these classrooms as *problem-driven*, for in the research laboratories, the problem does not merely situate or anchor learning, rather, it compels, provokes, and drives learning forward. This relentless need to move forward in a problem space is what we have tried to replicate into our classrooms. Thus, in the section that follows, we use PDL (problem-driven learning) to characterize these modified PBL environments. Following a socio-cognitive approach to classroom design, learning unfolds in the context of team interaction scaffolded [14] through probing questions offered by a faculty or post-doc facilitator whose job is to nudge the team in fruitful directions.

Following, we distill three essential principles we have applied to that translational process accompanied by text that resituates that principle in the lab context and then explains how we have translated that principle into the design of an introductory biomedical engineering classroom. Although these design principles for agentive learning environments derive from our studies of innovation communities in biomedical engineering, in formulating them and discussing them with learning researchers, we posit that they can guide the design of instructional settings in other areas. We are optimistic that instructors at all levels might embrace these principles for their value to bringing the excitement and motivation for science and engineering into the classroom.

Learning is driven by the need to solve complex problems.

Knowledge building in science and engineering is problem-driven. At the frontiers, potential solutions to problems lie within complex, adaptive problem spaces. Much of the research focuses on continually re-articulating the problem and determining tractable pieces through which progress can be made. In working toward solutions, multiple questions need to be addressed; multiple forms of activity need to be undertaken; and multiple forms of data generation, gathering, and analysis need to be undertaken. The complex, ill-defined nature of the problems promotes the distribution of problem solving activities across a community of researchers.

The introductory course in biomedical engineering engages second semester freshmen or first semester sophomore teams of eight with three different kinds of interdisciplinary problems over a fifteen-week semester. (See problems from fall 2011 at the end of paper). Variations of these problems are repeated each semester. The problems are complex enough that the efforts and talents of a team are required. What the students bring to the course is not uniform. Some might have taken advanced math and CS featuring Matlab. Some have taken statistics; others have not. There are transfer students from other majors or from others colleges programs that are participating in a dual degree program. In short, the teams are rather mixed in terms of prior experience and knowledge. To arrive at solutions in a five week time frame, multiple intermediate questions across varied disciplines need to be formulated and addressed. As an example, in problem 1, the cancer screening problem, student teams need to formulate and address questions concerning the biology of cancer, current screening technologies such at CT scans or MRI, future screening strategies at the nanoscale and probability statistics, among other topics. Questions addressing these areas drive the out-of-class research, which constitutes the preliminary data gathering. The various kinds of data then need to be analyzed, applied and then framed in the problem solution. In two of the problems, the teams generate hypotheses based on limited information and then develop mechanisms for testing the hypotheses. Knowledge accrues within individuals and across the teams in response to seeking a problem solution.

Interdisciplinary problems require lab members to work with interlocking models

In the labs we investigated, a common practice was to develop *in vitro* devices, or hybrid bioengineered models, that simulated specific aspects of the *in vivo* environment under investigation. As an example, in the vascular tissue engineering lab, a flow loop had been designed and developed to replicate certain mechanical properties, the impact of flow in arterial wall shear stresses, which the engineered vascular tissue would endure. To design and develop such complex devices, the interdisciplinary researcher needed what we call *interlocking models*[15]. Models interlock biological and engineering concepts, methods, and materials (interdisciplinary melding). Interlocking models are necessary for the design and construction of such devices that are able to straddle the *in vivo/in vitro* divide. The point is that in interdisciplinary contexts of work and research there is a convergence of multidisciplinary thought and action that creates the possibility to take on and solve new problems.

Each problem in the course is designed to foster the development of these interlocking models. Again returning to the cancer screening problem, students need to develop a biological model of cancer initiation and progression to a metastatic stage but then use this model to evaluate the technologies for screening. At the same time, statistical models of probability rendered in sensitivity/specificity and PPV values are the starting tools for analysis and evaluation. Students are facilitated in developing an analytical method for evaluating and making recommendations which could mean creating a numerical decision matrix or a formula that can be applied consistently to all screening methods both current and future. In other words, engineering problem solving approaches applied to qualitative, descriptive biological content, or put more simply, reasoning and problem solving like an engineer.

Learning is relational

Conducting research in science and engineering requires independence in forming relationships with people and artifacts. Research requires developing independence but interdependence as well. As we saw in the lab studies, a great deal of lab knowledge resides in the heads, experiences and notebooks of the various members. As repositories of scientific and engineering know-how, senior lab members become identified with specific lab devices, techniques, research questions, and evolving protocols, assays, and devices. Newcomers need to develop relationships with these people to get access to this knowledge. And in developing relationships, they learn about the senior lab members' experiences with particular devices and appropriate the requisite aspects of lab history that are often poorly chronicled in other places. With strong social relationships comes the potential for a wealth of problem-solving capacity and knowledge acquisition. But the lab newcomer has to develop the habit of first identifying and then going to people in the know.

Students in the PDL class need to identify potential partners and form relationships to arrive at a solution, for they cannot solve the problems alone. Obvious partners are the other team members, at first strangers but hopefully colleagues and friends as the term progresses. A successful team learns to see each member as a potential learning partner who both offers opportunities for learning but also is a learner him/herself. Other learning partners can be outside experts that the groups are encouraged to consult such as physicians, family members, faculty members, graduate students or post-docs working in labs as well as the faculty facilitator who guides the group. In providing a learning environment in which forming relationships is essential to success, students are ideally moving from a model of learning that privileges the single individual studying alone, to a model of socially-mediated learning.

Evaluation

The challenge with any new classroom approach is to design appropriate instruments to measure the desired learning outcomes. As this is the first course in the BME curriculum, it serves as an introductory methods course in reasoning and thinking in the context of interdisciplinary problems. The course starts the process of helping students develop interlocking models, new understandings of learning as forming relationships and a realization that authentic interdisciplinary problems can be the impetus for learning. Given the complexity of this PDL learning context and the fact that it seeks to develop skills rather than highly specified knowledge, we have attempted to collect various kinds of data to determine how well we are doing in fostering an interdisciplinary perspective and disposition. Assessment of student learning takes several forms.

- **Facilitator observation and evaluation:** Each team of eight has a faculty or post-doc facilitator that observes and facilitates the team for three hours each week. In these sessions they can observe and assess each student's behaviors as s/he interacts with, helps in the problem solving, works to develop knowledge and contributes through individual research to the process team. The assessment scoring sheet (See attached as appendix A, it the basis for grade assignment and is given to students the first day of class.
- **Team presentations and problem reports:** Each presentation and report has scoring sheets associated with it, which facilitators use to evaluate the work of their own team, but also the work of other teams. These are examples of performance-based assessment---assessment that is fully integrated into the classroom activities rather than standing apart such as a test.
- **Final exams:** We have also assessed the development of model-based reasoning in the students through analysis of the final exams which is a single problem requiring students to propose a method for addressing the problem. An analysis of two semesters of exams demonstrated that eighty-six percent of the students exhibited some form of model-based reasoning [16].
- **Alumna surveys:** In a recent survey which yielded a 60% return of graduates from the program, many alluded to the value of this class in terms of their current positions. Many also commented on the need to talk across disciplinary boundaries and that they felt well prepared to do this. One alumna quipped, "I am not afraid of anything anymore."

The course assessment rubric for the course can be found at the end of this paper.

Conclusion

Classroom activities that challenge old norms and redefine what it means to be a 21st century engineer [17] should aspire to creating opportunities to practice interdisciplinary reasoning and problem solving with potential positive effects both during a college career and after graduation. The kinds of problems engineering students will face after graduation will undoubtedly demand multidisciplinary expertise; the day of the sequestered engineer working alone on a problem is long gone, an artifact of the early 1990's when businesses "re-engineered" their practices. Today's areas for technological advancement can require electrical engineers to talk to chemical engineers as well as biologists, public health officials and policy makers, so students need to be prepared for these multidisciplinary work practices and exchanges. The students themselves are another reason to embrace greater interdisciplinarity in the classroom. Millenials bring a unique perspective and set of expectations annealed through extensive access to multiple forms of digital information. Characterized as being "confident", "team-oriented" and "achieving"[18,19], these students are eager even impatient to take on larger problems than those that can be found at the end of a chapter. As Internet voyagers, they are already border crossers, information foragers, so holding them to a single disciplinary approach or perspective can have alienating consequences resulting in even fewer students choosing engineering for a career. If our goal is to grow the number of engineers, to attract more women and minorities, we need new models for learning that better represent the hybrid nature of engineering and science that make these the arenas for innovation and discovery.

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APPENDIX A: Problem I

In 2009, The American Cancer Society estimated that 192,370 women would be diagnosed with invasive breast cancer and that approximately 40,170 women and 440 men would die from the disease. It is the most common cancer among women in each of five major population groups (White, black, Asian and Pacific Islanders, American Indians and Alaska Natives, and Hispanics) in the United States, and the second leading cause of cancer mortality for women in all major population groups with the exception of Hispanics, for whom it is ranked first. A striking divergence in long-term breast cancer mortality trends between African American and white women began in the early 1980s; by 2006, death rates were 38% higher in African American than white women Although routine mammograms for early detection of breast cancer are conducted widely in the United States, some have questioned whether these tests are effective in saving lives[1]. With an average sensitivity of 71.9%, specificity of 89.1%, PPV of 1.5% and recall of 10.9%, false positives have led to emotional distress and financial burden for many.

Your team has been selected by the American Association for Cancer Research (AACR) to investigate and to evaluate the current status of breast cancer screening I the United States, including the effectiveness of mammography. In addition, you are expected to identify and make recommendations regarding potential future screening strategies, which, relative to current strategies, improve sensitivity without sacrificing specificity.

[1] A H Olsen, A Jensen, S H Njor, E Villadsen, W Schwartz, I Vejborg, and E Lynge. Breast cancer incidence after the start of mammography screening in Denmark. *British Journal of Cancer* (2003) 88, 362 365.

Problem II

The latest data from the National Center for Health Statistics show that 66.3 percent of U.S. adults 20 years of age and older are overweight or obese. Excess levels of fat associated with obesity often lead to chronic health problems, which include high blood pressure, diabetes, coronary heart disease, arthritis, osteoporosis and various forms of cancer. By reducing the excess fat in the body, good health can be maintained. Thus it often becomes necessary to monitor the percentage of fat. An instrument specially designed for this purpose is the body fat analyzer. These instruments come in a variety of forms including special scales, and hand-held devices, but many are not as accurate as consumers would expect them to be if they are using them as part of a weight loss program.

Your group is to investigate potential sources of error in fat analyzers. You will first need to purchase (immediately!!) a device designed to analyze body fat content. In the next class meeting, take numerous readings in the group and see what you discover about the device. You are then challenged to develop a hypothesis concerning a factor, other than device malfunction or misuse, which contributes to one of a fat analyzer's low performance characteristics (e.g. accuracy, reproducibility or repeatability). You will then develop an experimental design to test that hypothesis. Your hypothesis should be formed based on a thorough study of both the physiology behind body measurements and the sensor technology employed in your device. Your experiment must be designed 1) to ensure the safety of your human subjects and 2) to use a sample size necessary to produce sufficient statistical power.

Problem III

HIV-AIDS threatens human health globally. The prohibitive costs of treatment and access to medical care in underdeveloped countries, side effects, compliance issues, rapid viral mutation, and the persistent impact of hard-to-reach high-risk viral "super-spreaders" make it unlikely that current approaches will halt the epidemic spread of HIV-1 viruses. A new treatment paradigm under consideration is the intentional infection of already HIV-infected or high-risk individuals with *Therapeutic Infectious Pseudoviruses* (TIPs)*. These bioengineered viruses can be designed to compete with the natural viruses for the host's replication machinery, while otherwise being harmless. Specifically, as the theory goes, TIPs can co-opt wild-type virus packaging elements, thereby decreasing disease-progression *in vivo* and reducing disease transmission on a population scale. Researchers have demonstrated that an anti-HIV TIP could potentially mutate with equal speed and under evolutionary selection maintain its parasitic relationship with wild-type virus, thereby overcoming viral mutational escape. Since TIPs replicate conditionally (i.e., piggyback), treatment compliance and cost issues would be eliminated. In theory, TIPs could be designed to transmit along a pathogen's normal transmission route, reaching precisely high-risk populations like drug users and sex workers.Your team has been hired to evaluate the effectiveness of this HIV hijacker approach for slowing or maybe even stopping the spread of disease by applying quantitative engineering analysis. You will need to 1) Create a mathematical model (perhaps by modifying or building on one or more existing models) that simulates the use of TIPs to address the spread of disease in a population. 2) Use the model to quantitatively evaluate the effectiveness of TIPs in addressing the spread of HIV-1 infection in a population by executing computational simulations of the interaction of TIPs and HIV under different model setting

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APPENDIX B: 1300 PBL ASSESSMENT RUBRIC

	EXCEPTIONAL (A	PROFICIENT (B)	FAIR (C)	POOR (D)
INQUIRY SKILLS	Actively looks for and recognizes inadequacies of existing knowledge Consistently seeks and asks probing questions Identifies learning needs & sets learning objectives Utilizes advanced search strategies Always evaluates inquiry by assessing reliability and appropriateness of sources	Recognizes inadequacies of existing knowledge Generally asks probing questions Utilizes appropriate search strategies Mostly evaluates inquiry by assessing reliability and appropriateness of sources Utilizes effective search strategies	Occasionally claims areas of inquiry but mostly takes what's left Occasionally asks questions Find easily available information of questionable reliability/ appropriateness	Takes whatever is left for inquiry Rarely, if ever asks questions Fails to recognize limits of understanding/knowledge Fails to assess the reliability or appropriateness of sources Demonstrates unsystematic search strategies
KNOWLEDGE BUILDING	Thoroughly digests findings and communicates effectively to self and others Consistently identifies deep principles for organizing knowledge as evidenced in research notebook Constructs an extensive and thorough knowledge base in all problem aspects Continually asks probing questions	Digest findings and communicates to self and others Identifies deep principles for organizing knowledge Constructs a thorough knowledge base in most problem aspects Asks probing questions	Reads inquiry results to group without thorough understanding of material Learns own area of inquiry but not those of others Occasionally asks questions	Fails to understand or be able to communicate inquiry findings Rarely if ever asks questions Fails to use the problem to develop/enhance BME knowledge
PROBLEM SOLVING	Repeatedly explores the problem statement to identify critical features Defines/redefines the problem and identifies problem goals Breaks problem down into appropriate parts Identifies and defines appropriate criteria Frequently uses white boards to assist in problem solving Consistently applies inquiry results to problem Develops models and hypotheses	Explores the problem statement to identify critical features Seeks to understand problem goals Identifies criteria Uses inquiry in problem solving Uses white boards to assist in problem-solving Occasionally develops models/ hypotheses	Relies on group to identify critical features Lets group identify problem goals and then follows along Sometimes applies inquiry to problem solving	Fails to define problem Articulates no problem goals Never uses the white boards Fails to apply inquiry to problem Never suggests a plan of attack Fails to develop analytic framework
TEAM SKILLS	Actively helps group develop team skills Willingly foregoes personal goals for group goals Always avoids contributing excessive or irrelevant information Consistently expresses disappointment or disagreement directly Consistently gives emotional support to others Clearly demonstrates enthusiasm and involvement Monitors group progress and facilitates interaction with other members Always completes tasks on time	Supports group goals Avoids contributing irrelevant information Expresses disagreement directly Gives emotional support to others Demonstrates enthusiasm and involvement Facilitates interaction with other members Completes tasks on time	Goes along with the group Follows but does not lead Avoids confrontation even when angry or frustrate Engages in limited interaction with other members Occasionally comes unprepared with no explanation	Does not help in developing team skills Gives no emotional or intellectual support to team Lets group down by failing to complete tasks Observes silently contributing little to process Shows little or no enthusiasm or involvement