Hierarchical Learning Ensembles

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Team Building for Undergraduate Scientists and Engineers

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We describe the design and implementation of our Hierarchical Learning Ensemble (HLE) model, a pedagogy that assembles interdisciplinary teams of graduate, undergraduate, and secondary-level students to solve science and engineering problems. Our goal is to sensitize undergraduates to working in heterogeneous groups and thus better prepare them for the workplace.

Introduction

Employers of science and engineering college graduates seek candidates who have some experience in the commercial sector. As teachers of undergraduates, we cannot provide such experience for our students. However, we can ask, “What skills are learned on the job that we are not currently instilling in our students?” One skill developed on the job, but not taught at academic institutions, is the ability to effectively work in heterogeneous groups. Thus, a gap exists in the training of undergraduate scientists and engineers: The curriculum fails to cultivate realistic team skills like those developed at the workplace.

To bridge this gap, we developed a pedagogy that prepares our students for the workplace by enhancing their ability to contribute to diverse workgroups. Our study is a collaborative effort between two undergraduate teachers—one teaching science education at a liberal arts college (~3,500 undergraduates, ~800 graduate students), the other specializing in biomedical engineering at a research university (~4,000 undergraduates, ~6,000 graduate students). We piloted our project with students majoring in biomedical engineering and education, but our method is broadly de-
signing so it can be applied to many scientific fields. The focus of this article is not the particular problem student teams were charged with solving; rather, we present a model whereby undergraduate teachers can impart team-building and group decision-making skills to their students.

Our pedagogy focuses on two dynamics: (1) We assemble multi-disciplinary teams, called Hierarchical Learning Ensembles (HLEs), of high school, undergraduate, and advanced graduate students for one week to solve scientific research questions cast in the spirit of Problem-Based Learning (PBL). HLEs capture the best aspects of each stage of intellectual development from secondary through graduate school. The younger students bring a bold sense of curiosity to their teams while the senior students gain an appreciation for distilling complex problems into elements that can be communicated to individuals with less training than their own. However, our HLEs are primarily designed to sensitize undergraduates to their future role as middlemen by creating workgroups that align with those found on the job. (2) With heterogeneous groupings, one problem lies in ensuring all members can contribute to the group experience. To address this problem, we implement our pedagogy in two distinct stages. In the first phase, which occurs before any HLEs are assembled, students conduct pre-ensemble laboratory exercises designed to impart specialized skills to participants. During the second phase, the HLEs are assembled for a one-week laboratory experience and charged with a PBL scenario: Synthesize a novel artificial material that can be used to replace human bone tissue. Our pedagogy is remarkable in that reasonable pre-activity (phase 1) allows diverse team members to make useful contributions to scientific research (phase 2).

Background
Science and engineering education in the United States is currently embracing a paradigm shift toward a team-oriented, real-world, design-based curriculum. The Accreditation Board for Engineering and Technology states universities must expect graduates to possess “an ability to design a system, component, or process to meet desired needs” (Engineering Accreditation Commission 1998). The National Science Foundation, National Research Council, U.S. Department of Education, American Society for Engineering Education, and other groups have all investigated the current state of science and engineering education and reached similar conclusions (Bordogna, Fromm, and Ernst 1993; Engineering Deans Council 1994; and National Science Foundation 1995). For example, the NRC’s Board on Education recommends universities “pursue undergraduate curricular reform, including early exposure to ‘real’ industrial practice, teamwork, and creative design” (National Research Council 1995). When integrating such reforms into the classroom, one critical decision facing the undergraduate teacher is that of team-formation. How do we form teams that teach students to work effectively in heterogeneous groups?

Today, PBL is a commonly adapted, cooperative learning, teaming strategy in which students work with open-ended problems. PBL is grounded in the premise that students learn concepts more effectively when connected to real-world situations (Morell et al. 2001; Herreid 2003). Though many versions of PBL exist, all PBL designs begin with a posed real-world query that challenges students to cooperatively generate solutions to the problem (Duch, Groh, and Allen 2001). PBL began at the McMaster University School of Medicine but has been adapted to a number of different disciplines, most notably at the University of Minnesota, University of Delaware, and Samford University (Boyer Commission 1998). Adaptations of PBL are especially suited for science and engineering programs because they help students develop skills and confidence for formulating problems they have not previously seen, and few professional scientists are paid to solve problems directly from the textbook or that have a single right answer (Arambula-Greenfield 1996; Duch 1996; Smith 1995). Given the current reforms in science and engineering education toward a more design-based, team-oriented curriculum, we infused a PBL-type challenge into our pedagogical model.

Implementation—Phase 1: Pre-ensemble activities
The first phase of our implementation plan occurred while undergraduate and high school classes were still in session. To recruit volunteers, we incorporated our pre-ensemble activities into existing courses and arranged for academic credit to be awarded to some of the participating students. We secured additional types of institutional support, including use of laboratories and stipends for some of the students to attend a conference of a professional society. Before any HLEs were formed, we met with students from each academic level separately to discuss the idea of a hierarchical work environment and the likelihood that they eventually they will be operating in such a structure. At these meetings, we conducted exercises to ensure participants share a common lexicon for describing biomaterials.

1 Graduate students: We met with the graduate students who, as future PhDs, assumed the roles of project managers and group moderators within the HLEs. We coached the graduate students to focus lower-level team members on specialized subskills and on the sharing of these specialties to the entire HLE. Because of their laboratory experience, the biomedical engineering students were designated as the technical leaders. The education students served as the group managers because of their extensive training in classroom management tech-
niques. The graduate participants were volunteers recruited from our research groups. Participating biomedical engineering graduate students fulfilled one of their three required teaching credits while the education graduate students were offered the opportunity to copresent our results at a national conference.

(2) Undergraduates: The engineering undergraduates conducted three laboratories designed to acquaint them with construction of biomaterials and molecular-scale nuances of self-assembling systems. These activities prepared the undergraduates to discuss biomedical concepts with other participants of differing achievement levels and were designed to illustrate how physical interactions can result separately in the formation of two of the structures found in normal bone: ordered collagen arrays and crystallized mineralities. The laboratories were entitled “Computer Simulation of Collagen Self-Assembly,” “Ordered Aggregation of Collagen Molecules,” and “Homogeneous Nucleation of Calcium Carbonate Crystals” and were inserted into the regular laboratory sessions of two courses at the research university, Structure of Biologic Materials and Materials for Prosthetic and Orthotic Use. The biomedical engineers were volunteers from these two classes.

The pre-ensemble activities for the education undergraduates had different goals. Focusing on their student teaching experiences and training in lesson planning, these participants developed two high school experiments designed to teach the secondary students about gelatin and measurement techniques. We presented our model in all educational methods courses at the liberal arts college and recruited volunteer student teachers. Over 200 student teachers were enrolled in these courses and 75% were female. Some student teacher participants earned one science independent-study credit.

(3) High school students: The student teachers then taught their two laboratory-based lessons to the high school volunteers. These laboratories instilled a sense of confidence in the high school students that they were indeed capable of constructing biomaterials but also provided a visceral intuition concerning the physical behavior of biomaterials and the macroscopic properties of gelatin. The laboratories were entitled “How Squishy Is Jell-O?” and “How Clear Is Jell-O?” To ensure a diverse group of high school participants, we visited several schools with greater than 50% minority student bodies. We addressed junior- and senior-level classrooms at each school and briefly discussed our project. After this initial contact, the student teachers returned to these schools to again present our project and finalize volunteers. High school participants received travel reimbursement, a stipend, free lunch, and a letter of recommendation from the research team.

Implementation—Phase 2: HLE formation

Once the semester ended, we enacted the second phase of our implementation strategy: the one-week summer program where HLEs grappled with an open-ended scientific research problem. Because of phase 1, student involvement in the HLE model was maximized. The high school students were able to contribute useful synthetic designs, the undergraduates were able to contribute theoretical insights, and the graduate students had strategies at their disposal to help manage the groups.

All 20 participants gathered early Monday morning. We separated the students into two HLEs, each consisting of 10 students: two graduate students, one in biomedical engineering and the other in education; two undergraduate biomedical engineers; two undergraduate student teachers; and four high school students. At this time, students were unaware of the challenge we had planned for them. We then introduced the problem the groups were charged with investigating—the design of a novel biomaterial. We acted as the owners of a small biotech firm while the HLEs played the role of two separate R & D teams at the firm. We pretended that a “corporate angel,” from whom we were seeking critical funding, was visiting our company in the near future. To prepare the firm, the two HLEs had to create their products and make presentations to the entire group by week’s end. The entire group would then select which components form the best product. Our intention was to create the feeling we were one company working as two independent groups on the same problem. The teams were then isolated from one another and given a laboratory, conference room, and stockroom access. Before leaving, we imposed only a few restrictions upon the teams: Each workday ran from 9 to 5 and included a lunch hour all participants were required to attend, the group was to constantly display a timeline containing personnel assignments and time constraints, and during the last 15 minutes of each day, all participants had to email us the “take-home message” from that day. We remained on the premises at all times and were available for consultation. The HLEs were then left to construct the composite and deliver their product to us by Friday afternoon. At the end of the week, both HLE teams successfully synthesized composite biomaterials. Our pre-ensemble activities and group deliverables are available on our website, www.jcu.edu/educatio/ccliai.htm.

Replication

The success of our project involves several components that allow our model to be replicated at other institutions without external support: (1) HLE teams are formed with students
from multiple disciplines. We accomplished this through a collaborative effort between neighboring colleges; however, it can be orchestrated between departments at one institution.

(2) HLE teams are formed with students of multiple achievement levels. Departments can recruit from their own pool of graduate and undergraduate students and join with local high schools to recruit secondary-level participants. (3) Pre-ensemble activities are first implemented to ensure all participants can contribute to group success. (4) Team formation is centered on a PBL-type research problem in which teams operate under a minimal set of constraints. (5) Finally, institutional support is crucial to the recruiting process and implementation plan. For instance, departments can offer participating students academic credit, letters of recommendation, stipends, or the opportunity to attend meetings of professional societies. Institutions must also make laboratories and equipment available to HLEs.

Evaluation
To ensure the objectivity, credibility, and success of the evaluation process, we utilized both internal and external evaluation strategies. The internal evaluation included an advisory panel of scientists and educators who reviewed the project’s implementation progress and impact on students. An external consultant evaluated our project based on self-reporting surveys. The evaluator conducted the following activities: overall evaluation guidance, development and statistical analyses of student surveys (pre, end of phase 1, end of phase 2, and follow-up), telephone interviews, and formative evaluation. A year-end report compared pre-project survey results to those from the follow-up surveys completed at the end of the summer workshop. Both surveys included open-ended items, but the summer workshop survey responses were especially informative regarding students’ experiences. An additional follow-up survey will be administered next semester.

Discussion
The students’ comments presented a very positive picture of their HLE experience. Although most did not have a clear idea of what to expect from the HLE project, and most feared not having sufficient prior knowledge, by project’s end all participants emphasized they did in fact successfully contribute to the group’s activities. Responses on the student surveys were grouped into the four categories discussed below:

(1) Teamwork: The project achieved its goal of assembling three different academic levels of students to simulate the workplace and allow participants to collaborate with individuals from a range of content specialties and skill levels. All participating students enjoyed the experience to a greater degree than they expected and would recommend it to a friend.

Ninety-three percent of the participants agreed the HLE experience had improved their ability to work collaboratively with others on a team project and to interact with diverse populations of individuals. Participants emphasized the single greatest benefit of the experience was their growth in understanding the importance of teamwork and their ability to work on a team: “This showed me how essential it is to have teamwork—many times someone came up with an idea no one else had.” Similarly, they grew in their appreciation of the role leadership plays in directing group activities, especially gaining an awareness for the challenge of working with team members from different disciplines and achievement levels: “It’s tough when we didn’t know how to proceed. The idea is getting different people to work like a well-oiled machine toward a common goal, but we were not always sure how to do this.” By the end of the session, 87% stressed the clear necessity of teamwork in scientific research.

(2) Perception of science: All participants found scientific research to be more competitive, open-ended, time-consuming, and complicated than their traditional curricula led them to believe. One interesting result that was clear to us during the summer experience, and that emerged from student surveys, was how a natural competitive spirit fueled the energy levels of both teams to create a highly charged and productive atmosphere. Though we did not intend for students to view the design challenge as a contest between the two HLEs, they exhibited a competitive desire to out-perform the other group: “This was more intense and energetic than I thought. By the end of the week, all we wanted to do was win.” Both groups adopted team names and slogans. One team went so far as to use some of their supply funds to buy team shirts.

The HLE experience also made participants more aware of the prevalence of open-ended problems in research and engineering: “Textbooks primarily provide specific questions that have specific answers. But really, scientists are exploring problems that have many answers.”

Additionally, students agreed the experience improved their opinion of scientists, engineers, and science as a career, making them realize scientists do much more than just “get the right answer.” Students explained: “I have a lot of respect for scientists and engineers—what they do is tough!” and “Scientists have a hard job. Science is a long and tedious process.” Eighty-seven percent of respondents confirmed the project’s positive impact on their perceptions of scientists and technically oriented careers.

The high school students gave the highest appraisal (75%) of the program’s impact on their future exploration of an engineering/technology-based profession.
Multiple achievement levels: Participants’ were unanimously enthusiastic about their coworkers, stating everyone was helpful, in some way, to the creation of the group’s product. For such a diverse group, everyone was personable and eager to establish a collegial atmosphere. Individuals were friendly, accessible, worked well with each other, and were able to establish a productive environment.

Feedback emphasized the graduate students were knowledgeable and were clearly perceived as the team leaders: “The grad students were great leaders and role models—they were so knowledgeable, intelligent, and respectful.” Predictably, comments on the undergraduates revealed these participants were viewed as middlemen. Graduate students found the undergraduates to be invaluable leadership partners: “They brought a different perspective to the group and helped keep us on track—at times, I would have been lost without them”; while high school students viewed them as peers, saying, “They were great fun to work with but were sometimes just as clueless as me!” Finally, the enthusiasm of the high school students was overwhelmingly synergistic. We had hoped the younger students’ excitement and curiosity would have a contagious effect on the more seasoned participants. Survey responses did not disappoint us: “The magic in the room was fueled by them,” and, “They worked really hard at solving this problem—their excitement rubbed-off on everyone.”

Multiple disciplines: Finally, participants were able to apply the HLE experience to their specialized disciplines. The education majors felt they could have assumed greater ownership over their projects but were too hesitant to do so because of lack of technical skills; however, they were pleased to be able to connect the experience to classroom instruction: “I would like to be able to set up something like this in my own classroom and be able to provide a similar experience for my students.” On the other hand, the biomedical engineers learned mostly about product development and connecting theory to practice: “Working in a team taught me to assume nothing and go over the basics before really digging in.”

Summary
In this study, we describe the Hierarchical Learning Ensemble (HLE) pedagogical model in which undergraduate students are presented with an experiential opportunity to function as middlemen in a realistic hierarchical work environment. Our pedagogy had positive impacts on participants’ appreciation of collaboration skills when working in scientific research, their perception of science as a profession, and their confidence in working with individuals from different disciplines and achievement levels.

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