2006-2664: CURRICULA TO EDUCATE THE 2020 MSE ENGINEERING PROFESSIONAL: SIMPLE BUT POWERFUL CHANGES IN THE WAY THAT MSE IS TAUGHT

Linda Vanasupa, California Polytechnic State University

Blair London, California Polytechnic State University

Katherine Chen, California Polytechnic State University

Richard Savage, California Polytechnic State University

Curricula to Educate the 2020 MSE Engineering Professional: Simple but powerful changes in the way that MSE is taught

Linda Vanasupa, Blair London, Katherine Chen, Richard Savage
Materials Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407, lvanasup@calpoly.edu, blondon@calpoly.edu, kcchen@calpoly.edu, rsavage@calpoly.edu

ABSTRACT

National leaders in science and technology sectors speak in unison as they call for engineers who are not only technically competent in their fields, but who possess the abilities to communicate well, to work on teams, to apply systems thinking, to operate in the global business environment, to design within a greater set of constraints (environmental, health and safety, sustainability, economic, societal, political, manufacturability, and ethical). In short, our challenge is to educate an engineering *professional* who is far more sophisticated than the *engineer* of the 20th century. Additionally, challenges brought on by the overuse of natural resources put a special responsibility on materials science and engineering (MSE) faculty, whose role it is to assist in shaping the MSE profession. How can faculty deliver relevant curricula for the MSE engineering professional in an already crowded curriculum? Certainly curricular content must be up-to-date. However, a number of the goals can be met through changing the way in which the curriculum is delivered. In particular, we have emphasized mastery at the lower levels to increase retention, and implemented a number of learning "best practices". Our preliminary results are promising: within one year, we were able to reverse a five-year trend in declining enrollment; we have just finished our fourth consecutive year of 100% on-time completions of senior projects; students exhibit a shift in mindset towards a greater awareness of their professional responsibility to serve humanity. In this paper, we will provide a survey of the techniques that we have used along with some preliminary results from our program.

INTRODUCTION

Globalization, the information age and prosperity have come together in the late 20th century to create a host of challenges that threaten the survival of the planet and its inhabitants. The danger signs are everywhere: ubiquitous toxins that damage the animal and human reproductive prospect[1]; global-scale non-renewable use of natural resources[2]; and the looming end to readily-available fossil fuels[3], which largely run the global economic machine. Many of our problems have been inadvertently brought on by way of advances in technology. The key to meeting these challenges, as Einstein has warned, lies in ways of thinking that are different from the ones that created the problems. The engineers of the 21st century must be able to see the interconnectedness of society, technology and ecosystems. They must be aware of a set of design constraints that extends beyond the economic and technical aspects of an engineered product. The need for a more sophisticated *engineering professional* is expressed in part through the Accreditation Board for Engineering and Technology (ABET) 2005 accreditation criteria, elevating the role of global, environmental, sustainability, society, ethical, health and safety issues in engineering programs[4]. These engineers, working together across the disciplines, will hopefully bring about a sustainable world economy.

According to the *World Health Organization's Millenium Ecosystem Assessment,* roughly 60% of the earth's ecosystems are being used faster than they can be replenished[5] [5]. Materials engineers could play a critical role in developing more sustainable materials and material processes. However, to do so, these engineers must not only possess the abilities to communicate well and to work on teams, but they should be able to apply systems thinking, operate in the global business environment, and design within a greater set of constraints. At Cal Poly, we have implemented the first two years of a 4-year phase-in of a new materials engineering curriculum; it aims to build the core competencies of the materials engineer through utilization of educational best-practices, presentation of systems viewpoints and emphasis on design. In this paper, we discuss the attributes of our curriculum design and provide some data on its effectiveness to date.

OVERVIEW OF CURRICULUM

Like many engineering curricula, ours begins with a primary focus on general education (math, science, liberal arts). As shown in Figure 1, roughly 25% of the units in the curriculum are in the area of liberal arts, 35% in engineering support courses (math, science, engineering science) and the remainder in materials engineering (MATE) courses. The proportion of MATE courses increases in the junior and senior years. The general layout and proportions are similar to many MSE programs. However, to counterbalance high rates of attrition within the first two years, we have replaced a freshman "seminar" with a year-long design course. This course plays the critical role of keeping students engaged in engineering while giving them experiences that have been shown to promote retention (see discussion below under "Utilization of Best Practices").

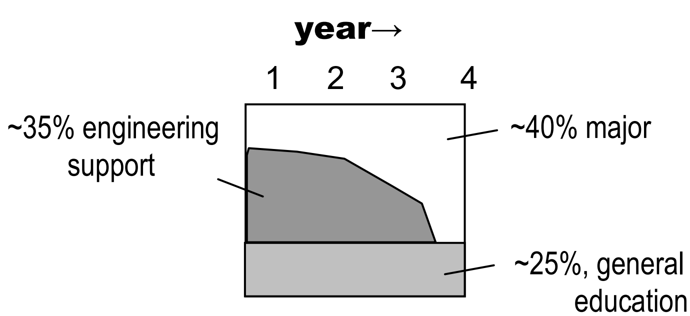

Figure 1. Distribution of courses within the materials engineering curriculum.

Each year of the curriculum has themes that we plan to emphasize. These are shown in Figure 2. In the first two years, we emphasize engineering basics and systems thinking. Two courses in the sophomore year have been added to promote these themes and two existing laboratories were adjusted. The two sophomore-level courses are *Materials Selection for the Life Cycle,* and *Nanotechnology, Biology, Ethics and Society*. Both courses emphasize systems thinking, the first in the design process, the second through articulating the interconnectedness of the topics within the course title.

The third year (which we will implement in Fall 2006) is dedicated to process design and control. In the past, the junior year was dedicated to courses like "Materials Thermodynamics," "Mechanical Behavior of Materials," and "Electronic Properties of Materials." We have replaced all of these topic-based courses with project-based courses, where students will learn the materials science and engineering in the context of working on a larger project. The senior year is dedicated to building professional depth and breadth along with a guided year-long

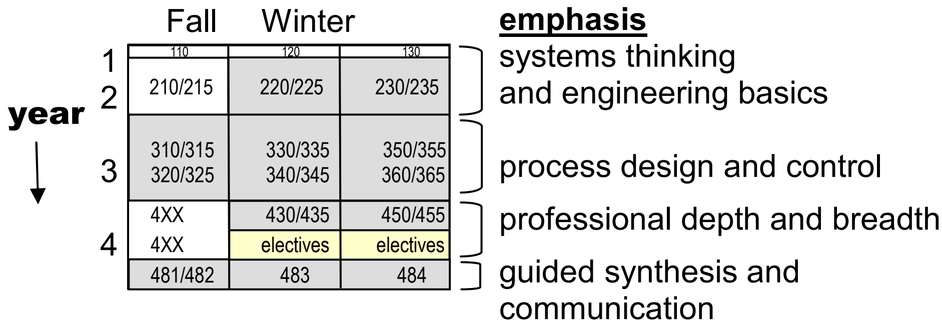

Figure 2. Layout of major courses within the curriculum (support and general education courses not shown in this figure). The size of the boxes are proportional to the number of units in the course. For example, the 110 course is 1 quarter unit, while the 210/215 course is 4 and the 310/315/320/325 is worth 8 quarter units.

capstone design experience that is designed to develop students synthesis and communication skills. We have shifted our capstone experience to a guided design process that is more akin to project management in industry.

UTILIZATION OF BEST PRACTICES

To accomplish our objectives, we have chosen to incorporate eight "best practices" of education within our curricular approach. The eight best practices are depicted in Figure 3 and discussed below.

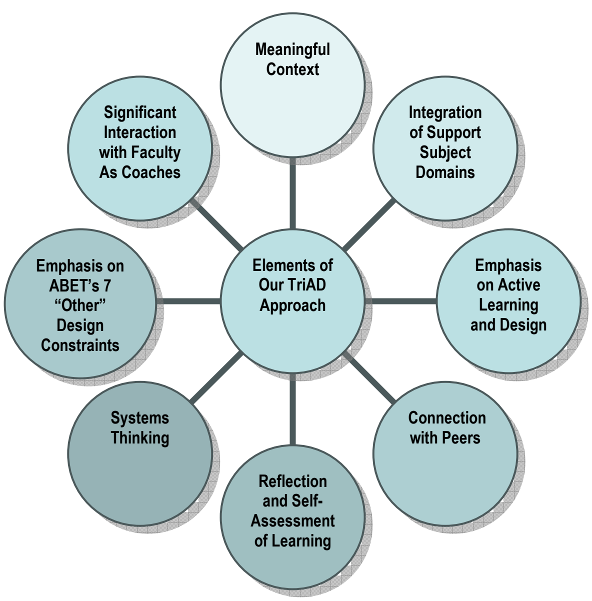

Figure 3. Eight "best practices" in our approach

1. **Meaningful Context:** Seasoned teachers such as John Gatto and David Orr have criticized education in the U.S. for its lack of meaningful context;[6,7] subjects are often taught in such a way that makes them seem irrelevant to everyday life. In our curriculum, we borrow from the principles of *service learning*, in which the learners are engaged in experiential learning that addresses human and community needs.

Engineering students involved in service learning demonstrate a stronger ethic of social and civic responsibility,[8] develop empathy for others,[9] demonstrate greater personal growth (maturity) and develop a broader appreciation of non-technical concerns and the impact of technology on society.[10]

Our hope in providing a balanced degree of meaningful context is to increase the retention of women in engineering. According to the *Women's Experiences in College Engineering*

Project (commonly known as the *WECE Project*), women who choose engineering as a profession often do so out of a desire to help society.[11] However, it is rare for curricula to contain clear connections between the engineering profession and helping society, which may contribute to attrition of female engineering students. Faculty at Smith College found that service learning provided meaning for female students in engineering.[12] Lima of Louisiana State University found that service learning increased the retention rate of the female engineering students to 93% (the national average is ~70% when measured from the junior year to graduation).[13]

In addition to aiding retention, we believe that the meaningful context of addressing a community need will enhance the motivation to learn the foundational subjects (math, science, communication); research has shown that feeling that one is contributing something to others is especially motivating.[14] Unsurprisingly, motivation strongly affects the amount of time one is willing to devote to learning,[15] and time is a critical element in learning a new subject.[16]

2. **Integration of Subject Domains from Support Courses:** Traditional engineering curricula are often experienced by the students as a series of difficult, unrelated courses. The lack of subject cohesiveness in the first two years surely contributes to the 60+% national attrition rate in engineering. Engineering education leaders have long called upon faculty to do a better job of integrating science, math and communication in the engineering curricula.[17,18,19] In 1995, the National Research Council's (NRC) Board on Engineering Education called upon all engineering colleges to provide more exposure to interdisciplinary/cross-disciplinary aspects of teamwork, hands-on experience, creative design, and exposure to "real" engineering and industrial practices, identifying integration of key fundamental concepts in science and engineering as the number-one principle for new engineering curricula and culture.[20] Ideally, entire curricula would comprehensively integrate these subjects. However, integrating these subject domains into engineering is most critical at the freshman level; unsurprisingly, students (and especially women) are most likely to leave engineering majors during the freshman or sophomore year.[21] The type of integrated, activity-based design courses that we implemented in the freshman-year lab has been shown to be especially effective at retaining women and other underrepresented groups.[22]

   By integrating the topics from the support courses, we also hope to minimize a common, negative result of the typical engineering curriculum. We faculty assume that students will internally connect the information that is "input" into them during their studies. We expect that students will be able to apply their sum total of knowledge on their senior project, without previously being required to do so. Integration exposes the students to the concept of *transfer* (i.e., the ability to apply concepts learned in one context to problems in another) across subject domains.[23] Transfer of support subject domains is critical to the success of an effective engineer. By providing early exposure to transfer and examples of other contexts in which the principles are applicable, learners are more likely to transfer principles to different contexts[24] and practice transfer in general.

3. **Emphasis on Active Learning and Design:** Cal Poly's motto, "Learn by Doing," is embodied in our laboratory-intensive curricula; about one half of the MATE major's course time is spent in laboratories, versus about 10% or less in comparable engineering degree programs at other state institutions. Our experience with active learning methods confirms the results of others (for example, Springer, Stanne and Donovan[25] or Colbeck, Campbell and

Bjorklund[26]) who have found that interactive-learning classroom techniques promote *deeper learning*. With deeper learning, students retain the concepts and are better equipped to accurately transfer the principles to new situations.

Design employs the design method. Most students have been schooled in the scientific method, which is primarily focused on testing hypotheses. This is an excellent foundation for the design process, but the goal of the scientific method is to expand knowledge, whereas the goal of the design method is to build a device or process. Accordingly, in the design method, one must first define the application and performance specifications of the product in terms of functional requirements (FR). These FR's must then be broken down into specific design requirements (DR), and a design solution that meets these DR's must be created. A full-blown engineering design demands advanced knowledge and skill, so the freshman version of design is scaled back. However, we believe that exposing the freshmen to a holistic design methodology will help set the stage for more complex problem solving later in their studies.

4. **Connection with Peers:** The *WECE Project* indicates that enabling female students to establish support networks is vital to their persistence in engineering.[27] Our department has a 50-67% retention rate for female students, compared to the College of Engineering average of 50%. We feel fortunate to have established what researchers call a *learning community*[28] in our department. It is an atmosphere in which students help one another solve problems and encourage each other toward their goals. The freshman year design experience aims to build learning communities within the class cohort.
5. **Reflection and Self-Assessment of Learning:** Reflection is one of the essential components of *service learning*[29,30] and of a student's ability to assess his or her learning. Also, teaching students to monitor their own learning should be integrated into the curriculum if the goals are to develop problem-solving skills and enable the students to engage in life-long learning.[31]
6. **Systems Thinking:** Systems thinking emphasizes seeing the whole and establishing a framework for seeing inter-relationships rather than individual things—for seeing patterns of change rather than static conditions.[32] Many have identified the need for this type of education in design.[33,34,35] We are promoting systems thinking through repeatedly presenting systems within our courses. Another method that we have been utilizing is an emphasis on graphical depictions of events and patterns as suggested by system dynamics practitioners.[36,37] Currently, we have not assessed whether this approach promotes more holistic thinking.

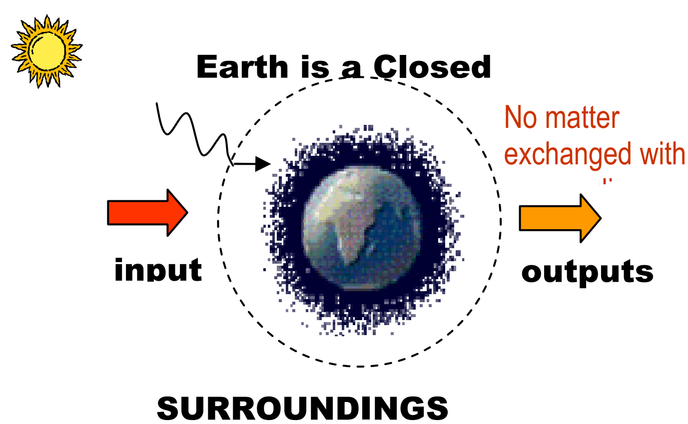

Figure 4. Earth is essentially a closed system. Energy can enter and exit, but no matter can enter

However, we have found that simple depictions of systems can have profound shifts in students' thinking. Early in the Fall 2003 offering of MATE110, the students were given predictive data on global warming that indicates the potentially disastrous climate changes that could await us in about 100 years When asked to brainstorm ways in which they could prevent the disaster as an engineer, students' first responses were comments like, "What does it matter? I'll be dead by then," and "You can't tell people how to live." However, after being presented with some simple systems ideas (i.e., Earth is a closed system, vehicles are open systems), the same group of students saw the connection and were able to come up with a number of ways in which engineers could make a difference.

7. **Emphasis on ABET's 7 "Other" Design Constraints:** While programs often require a course in engineering economics, the seven other design constraints (environmental, societal, health and safety, manufacturability, sustainability, ethical, and political) are often de-emphasized. Yet many experienced engineers, such as Gene Moriarty, recognize that these other constraints are *essential* to the design process.[38] The exercises that we have built into the curriculum draw on the fundamental principles in addressing the seven other design constraints for the purpose of promoting holistic, systems thinking.
8. **Significant Interaction with Faculty as Coaches:** Faculty interaction and feedback play vital roles in whether engineering students gain skills.[39] However, too often the lecture mode of learning implicitly promotes the "sage on the stage" idea: Faculty are all-knowing. The unfortunate result is that students adopt the idea of turning to the experts for "right" answers, rather than discovering solutions on their own. The beauty of real-world design projects is that there are several "right" answers. In fact, novice learners may have an advantage in coming up with fresh ideas, as they are not predisposed to limit their thinking. As a result, all team members are on more equal footing, including the faculty. In our design projects, faculty participate in the teams as coaches, rather than as the ones with the answers, which is an important element of a successful service learning experience.

PRELIMINARY RESULTS

As stated earlier, we are in the second year of our 4-year curricular phase-in. At the time of this writing, we have had two cohorts of 35-45 students in the freshman year design lab. We are currently teaching the *Material Selection for the Life Cycle*, and the adjusted sophomore-level labs. In testing the performance of the first cohort, our findings on shifts in students' understanding (published elsewhere in detail) were encouraging. Their understanding, testing at the beginning and end of the freshman lab sequence, shifted from a lack of awareness to: 1) recognizing that the foundation of the engineering profession is to improve the welfare of humanity; 2. recognizing global issues facing the engineering profession; 3. recognizing that the earth has limited resources. Also, faculty observed differences in students' ability to think critically after completing exercises designed to promote systems thinking. Whether these shifts in mindsets will affect the engineers' decisions and behavior over time is unknown. However, the measured success in changing students' perspective through these classroom techniques is hopeful.

The first cohort in the freshman experience showed us a number of things to avoid. For example, as some of the clients for the service learning project, we had wealthy individuals who were building their dream homes. Our students were meant to bring their well water up to drinking quality standards. Students serving the wealthy clients had a negative motivation to "help" them, as they felt there was no real need. This year, we have adjusted one of the design projects so that it is meant for individuals in a catastrophic disaster, like a tsunami or a category 5 hurricane.

At the time of this writing, we have only completed a third of the second freshman cohort experience. However, surveys of the students after the first quarter of their freshman sequence show that we have successfully begun to build strong connections with their peers, helped them see the value of their "engineering support" courses, given them hands-on experience with engineering and design, and enabled them to pick up useful skills. Roughly three fourths of the students indicated that the course gave them more confidence in their potential engineering abilities. However, at this point, we are less successful at motivating them to study in their other courses.

Table 1. Summary of some of the survey results for the second cohort in the freshman design sequence.
39/43 said that taking the class has helped them develop strong connections with peers (note, one 7-member group had a bad experience) 36/43 said that this class helped them see the value of other courses 20/43 said that this class motivated them to study more in their other courses, 23/43 said it did not. 42/43 said that taking the class give them hands-on experience with engineering (1 abstained) 30/43 said that the course has given them more confidence in their potential engineering abilities (please note that 1 strongly disagreed, 11 disagreed and that many came into the course with a high level of confidence that they engineering was right for them). 38/43 said that they picked up useful skills in the course 43/43 said that the course gave them more experience with the design process

The data paints an encouraging picture: we are achieving in part, some of our goals. However, the real evidence is through the retention figures. Like other engineering programs, ours experiences an attrition rate from the freshman to the junior year of 50-65%. The first two years are critical and most of the individuals who drop do so by the second quarter of their sophomore year. For example, a freshman class of 40 students will be a junior class of 20-22 students after two years. At the time of this writing, our 2004 freshman cohort of 36 is now a sophomore class of 34. Although we have lost about 6 students from the initial 2004 cohort, we have also had freshman and sophomore students transfer into the 2004 freshman cohort. The 44-member 2005 freshman cohort has seen an influx of six students, five of whom are females.

The senior design sequence has yielded positive results in the form of 100% on-time completion and higher quality of senior projects. At the time of this writing, we have just completed the fourth consecutive year of our success with the senior projects.

FACULTY BUY-IN

At the time of this writing, we have officially team-taught four courses, with the faculty participating jointly in the decisions, and are about to begin a fifth course. Although all participating faculty have embraced the idea of team teaching and the larger curricular goals, frankly, this has been a bit of a rocky transition, requiring us to seek the assistance of one organizational psychologist and a behavioral psychologist. This summer, we will undertake the most significant of the changes, the junior course series ("year 3"). We expect to need the assistance of the psychologists throughout the teaming process, as functioning on a team is not natural for faculty. We are all aware of the irony that we expect it from our students but are having great difficulty ourselves.

The transition from to the role of "coaches" from "sages," challenges each of us uniquely. The unfolding challenges are likely to be the most challenging aspect of our new curriculum.

SUMMARY

While maintaining a broad curriculum on materials engineering, we have been able to shift the educational approaches and some of the content to promote the development of the *engineering professional*. These shifts have also resulted in a number of measurable benefits, including greater retention of underrepresented individuals, and shifts in thinking toward greater awareness of global issues. Although our approach to teaching and learning has changed in small ways, it is powerful in both changing students' attitudes and in engaging them in their own learning.

ACKNOWLEDGEMENTS

This work was made possible in part by a grant from the National Science Foundation (Grant Number EEC-0530760).

REFERENCES

[1] Colborn, T., D. Dumanoski, J.P. Myers, *Our Stolen Future*, Penguin Books, New York (1997).

[2] Wackernagel, M., N.B. Schulz, D. Deumling, A. Callejas Linares, M. Jenkins, V. Kapos, C. Monfreda, J. Loh, N. Myers, R. Nargaard, and J. Randers, "Tracking the Ecological Overshoot of the Human Economy," *Proceedings of the National Academies of Sciences* 99 (2002): 9266-9271.

[3] Goodstein, David, *Out of Gas: The End of the Age of Oil* (New York: W.W. Norton and Company, 2004) 128.

[4] Engineering Accreditation Commission, *Criteria for Accrediting Engineering Programs*, (Baltimore, MD: ABET, Inc., 2005): 2.

[5] *Ecosystems and human well-being: health synthesis: a report of the Millenium Ecosystem Assessment*, World Health Organization, Core Writing Team: Carlos Corvalan, Simon Hales, Anthony McMichael; extended writing team: Colin Butler *et al.*; review editors: José Sarukhán, *et al.*: WHO Press, Geneva, Switzerland (2005): ii.

[6] Gatto, J.T., *Dumbing Us Down: The Hidden Curriculum of Compulsory Schooling* (Canada: New Society Publishers, 1991): 1-20.

[7] Orr 94-103.

[8] Honnet, E.P. and S.J. Poulsen, *Principles of Good Practice for Combining Service and Learning: A Wingspread Special Report*, reprinted by the National Service-Learning Cooperative Clearinghouse with permission from the Johnson Foundation, Inc., www.servicelearning.org/article/archive/87/.

[9] Brackin, P. and J.D. Gibson, "Capstone Design Projects: Enabling the Disabled," *Proc. 2002 ASEE Conference.*

[10] Slivovsky, L.A., F.R. DeRego Jr., L.H. Jamieson, and W.C. Oakes, "Developing the Reflection Component in the EPICS Model of Engineering Service Learning," *Proc. 33rd ASEE/IEEE Frontiers in Education Conference*, Boulder, CO, 2003.

[11] Goodman Research Group, Inc., "Executive Summary," *The Women's Experiences in College Engineering Project* (Cambridge, MA): xi.

[12] "First Class Program at Smith College," *ASEE PRISM* (Summer 2004): 17.

[13] Lima, M., "Service Learning: A Unique Perspective on Engineering Education," *Projects That Matter: Concepts and Models for Service Learning in Engineering* (American Association for Higher Education, 2000): 114-118.

[14] Schwartz, D.L., X. Lin, S. Brophy, and J.D. Bransford, "Toward the Development of Flexibly Adaptive Instructional Designs," *Instructional Design Theories and Models: Volume II,* ed. C.M. Reigelut (Hillsdale, NJ: Erlbaum, 1999): 183-213.

[15] Committee on Developments in the Science of Learning and Committee on Learning Research and Educational Practice, *How People Learn: Brain, Mind, Experience, and School, Expanded ed*., ed. J.D. Bransford, Commission on Behavioral and Social Sciences and Education (Washington, DC: National Research Council, 2000): 60.

[16] Committee on Developments in the Science of Learning and Committee on Learning Research and Educational Practice 59.

[17] National Science Board Task Committee on Undergraduate Science and Engineering Education, *Undergraduate Science, Mathematics, and Engineering Education*, (Washington, DC: National Science Board, 1986).

[18] *Engineering Education Answers the Challenge of the Future* (Washington, DC: National Congress on Engineering Education, 1986).

[19] *A National Action Agenda for Engineering Education* (Washington, DC: American Society for Engineering Education, 1987).

[20] Board on Engineering Education, *Engineering Education: Designing an Adaptive System* (Washington D.C.: National Academy of Sciences, National Research Council, 1995).

[21] Goodman Research Group, Inc. x.

[22] Hoit, M. and M. Ohland, "The Impact of a Discipline-Based Introduction to Engineering Course on Improving Retention," *J. Engineering Education* 87 (1998): 79.

[23] Committee on Developments in the Science of Learning and Committee on Learning Research and Educational Practice 17.

[24] Bjork, R.A. and A. Richardson-Klavhen, "On the Puzzling Relationship between Context and Human Memory," *Current Issues in Cognitive Processes: The Tulane Flowerree Symposium on Cognition,* ed. C. Izawa (Hillsdale, NJ: Erlbaum, 1989).

[25] Springer, L., M.E. Stanne, and S.S. Donovan, "Effects of Small-Group Learning on Undergraduates in Science, Mathematics, Engineering, and Technology: A Meta-Analysis," *Review of Educational Research* 69 (1999): 1-21.

[26] Bolbeck, C.L., S.E. Campbell, and S.A. Bjorklund, "Grouping in the Dark," *J. Higher Education* 71 (2000): 1-16.

[27] Goodman Research Group, Inc. xii.

[28] Committee on Developments in the Science of Learning and Committee on Learning Research and Educational Practice 25.

[29] Eyler, J., and D. Giles, *Where's the Learning in Service-Learning?* (San Francisco: Jossey-Bass, 1999): 1-22.

[30] Duffy, J., E. Tsang, and S. Lord, "Service Learning in Engineering: What, Why, and How?" *Proc. American Society for Engineering Education Annual Conference,* 2000 (CD ROM).

[31] Committee on Developments in the Science of Learning and Committee on Learning Research and Educational Practice 21.

[32] P. Senge, The Fifth Discipline: The Art and Practice of the Learning Organization (New York: Doubleday, 1990).

[33] Fromm, E. "The Changing Engineering Education Paradigm," *J. Engineering Education* 92 (2003): 113-127.

[34] Splitt, Frank G. “Environmentally Smart Engineering Education: A Brief on a Paradigm in Progress,” *J. Engineering Education* 91 (2002): 447-450.

[35] Hawkins, P., A. Lovins, and L.H. Lovins, *Natural Capitalism: Creating the Next Industrial Revolution* (New York: Little, Brown and Company, 1999): 19.

[36] Anderson, V. and L. Johnson, *Systems Thinking Basics: From Concepts to Causal Loops* (Waltham, MA: Pegasus Communications, Inc., 1997).

[37] Richmond, B. “Systems thinking: critical thinking skills for the 1990s and beyond,” *Systems Dynamics Review* 9 (1993): 113-133.

[38] Moriarty 140.

[39] Bjorklund, S.A., J.M. Parente, and D. Sathianathan, “Effects of Faculty Interaction and Feedback on Gains in Students Skills,” *J. Engineering Education* 93 (2004): 153-160.