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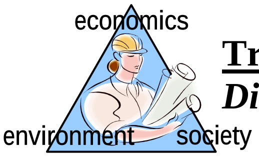

Triple Bottom Line Awareness in Design (TriAD):

Diversifying the engineering profession of the 21st century

Goals and Objectives

We propose to **advance the knowledge of how to design engineering learning experiences that accomplish two social imperatives**: 1. retaining women and other underrepresented groups in the engineering degree programs; and 2. equipping engineers to solve the technical challenges in the context of our complex global society.

Our strategy is to apply the rich body of results and best practices from education research on the re-design of a curriculum that emphasizes what we are calling **Tri**ple Bottom Line **A**wareness in **D**esign (**TriAD**)—the necessity of considering not only economics, but the broader issues of environmental impact and social needs in the design process. We will refer to our strategy as "the TriAD curricular approach." Although the curriculum is specifically for materials engineering, we feel that the TriAD design elements can be generalized to apply to other programs.

The **broader goals** of our proposed activities are to:

- Empower and retain underrepresented individuals by enabling them to experience early mastery of appropriate challenges and develop strong connections with peers;
- Birth a new breed of engineers who are holistically-oriented systems thinkers who embrace the engineering professions' ethic of applying their knowledge to benefit humanity (i.e., the "engineer of the 21st century");
- Motivate engineering students to study by providing a larger purpose and role in society;
- Enhance the initial learning of engineering students' supporting subjects (math, science, communication) by engaging them in experiences that have clear connections to the supporting subjects;
- Improve engineering students' ability to transfer their knowledge to subject domains beyond the one in which the knowledge was acquired (e.g., apply statistics principles to engineering solutions);
- Inspire engineering students to make a positive contribution to society;
- Cultivate in students the responsibility for and ability to monitor their own learning process;
- Encourage faculty at other institutions to implement sustainability design principles within engineering curricula;
- Facilitate the adoption of effectual learning experiences by other engineering programs.

The **measurable objectives** of our proposed research are to:

1. Demonstrate the effectiveness of the TriAD curricular approach in developing systems thinking, a sense of professional responsibility, and awareness of global challenges and design constraints required for the engineer of the 21st century;
2. Demonstrate the effectiveness of the TriAD curricular approach in retaining underrepresented groups in engineering programs;
3. Demonstrate the effectiveness of existing web-based tutorial programs at the pre-college level in improving the success of at-risk underrepresented groups in math and science at the college level;
4. Provide educational materials for the larger academic community to enable the adaptation/adoption of effective practices.

Rationale:

The 21st century requires a new breed of engineers

> "This is the century when human beings must learn how to live on this planet in an environmentally sustainable way."
>
> *-John Hennesy, President and electrical engineer, Stanford University, on establishing* The Stanford Institute for the Environment, *March 2004*

Although there is no consensus on the exact timeline, many well-recognized scientific leaders believe that the global community is destined for a catastrophic energy and environmental crisis within this century if leading industrialized nations do not take immediate steps to radically decrease the rate at which human activity damages the biosphere. According to Wackernagel *et al*., the global population is currently consuming natural resources at a rate of 120% of what the earth can regenerate.[1] David

> "The world will not evolve beyond its present state of crisis by using the same thinking that created the situation."
>
> *-Albert Einstein*

Goodstein, professor of physics and provost of Cal Tech, assesses the present state of fossil fuel reserves and predicts that we will deplete the earth's fossil fuels within the next 40-100 years.[2] Our propensity for consuming fossil fuels has accelerated the melting of the polar ice caps within the last 20 years, aggravated by the rapid accumulation of atmospheric greenhouse gases.[3] Because we have already damaged key components of the biosphere such as forests, waterways, fisheries and the ozone layer, we cannot forestall action. Indeed, over 300 university presidents have underscored the urgency of change by signing the *Talloires Declaration*.[4] In it, university leaders call attention to the precarious state of the environment *and* global society, as all life and activity in the biosphere depends critically on a healthy environment. The *Talloires Declaration* calls for immediate action, including developing and deploying environmentally preferable technologies, to ensure a more sustainable future for all humanity.

Historically, environmental initiatives within engineering have mainly been isolated within environmental engineering. However, approaches to meeting economic and social demands amid tighter environmental constraints have been evolving over the last 30 years. Indeed, as the international community has been examining the scope of the problem—depleting natural resources, diminishing biodiversity, social inequity—it is clear that sustainable solutions will require knowledge from all disciplines. There are no magic bullets. There are no simple solutions. What is required is new thinking, new ideas…new ways of balancing **economics**, the **environment**, and **social imperatives.** The idea of balancing these three is a principle in sustainability.[5,6] It is often called the ***triple bottom line***. As David W. Orr states in his book *Earth in Mind: On Education, Environment and the Human Prospect*, "No generation has ever faced a more daunting agenda."[7] We believe that this **requires a new breed of engineers**—those who are not only technically competent, but who have developed a greater understanding and compassion for the biosphere and its inhabitants[8] and embrace the service role they play in the global community.

Technical challenges of a diverse society require a diverse engineering profession

It is incumbent upon engineers, whose business is the innovation and management of technology, to provide new and creative ideas in the global community's quest for sustainable solutions. Yet along with the urgent need for a new breed of engineers, there is a compelling need for engineering to reflect the society that it serves. Why? Gender and ethnicity are such defining factors that they uniquely influence one's perspective and concerns. Although the concerns may overlap for different groups, more often than not, they are distinct. A profession's collective decisions and actions emerge from the members' concerns. If a profession is dominated by one group, as is the case for engineering, the social concern from which the profession acts is diminished. Technological advances have contributed to compelling social needs (partially described above), yet there is a danger that these needs will not be addressed unless the engineering profession changes to reflect the greater society and its larger concerns.

Despite a multitude of efforts within higher education to change the demographic of the engineering profession over the last 25 years, women and ethnic minorities continue to be underrepresented in the U.S. engineering profession. Although there are regional successes such as the *Louis Stokes Alliance for Minority Participation,*[9] on the whole the **engineering academic community needs a greater understanding of how to design learning experiences that foster retention of underrepresented groups.**

Sustainability impassions youth and fosters new approaches to engineering

Declining U.S. graduation rates in engineering portend a bleak picture of our ability to meet society's challenges. Furthermore, current U.S. engineering curricula, with their disciplinary isolation, built-in resistance to change[10] and emphasis on the economic "bottom line,"[11] hinder the empathetic, holistic thinking that is needed to overcome our challenges. Some engineering faculty believe that today's youth are not interested in learning a difficult subject like engineering. However, we believe, as Dr. Orr does, that young people will be motivated to study and apply their creative energies to benefit society if they are aware of the need and know they can make a difference.

We believe that **approaching the engineering design process with the goal of balancing the triple bottom line while applying the collective research from the learning domain has the power to reverse declining enrollment trends in engineering.** In essence, the sustainability movement is the civil rights movement of the 21st century on a global scale; it calls for social justice for all citizens of the planet and actions by governments to ensure a healthy environment. Certainly, outside the U.S. many nations have embraced sustainability as the only way to ensure quality of life for future generations.[12,13] The evidence that sustainability has this power among the youth in the U.S. is seen in the ground swell of grassroots student organizations[14,15,16,17,18] like *Energy Action: Youth United* *for Clean Energy.*[19] In the past nine months, these organizations across the U.S. have joined together and authored a *Declaration of Independence from Dirty Energy,*[20] which they delivered to Congress and state leaders in 2004. Their passion for and commitment to global environmental health and social justice for all is clear.

Research questions:

Research question 1:

Is the TriAD curricular approach effective in developing systems thinking, a sense of professional responsibility, awareness of global challenges and design constraints required for the engineer of the 21st century?

That is, does it:

1. Effect a greater awareness of engineers' professional responsibility to apply their knowledge to benefit society;
2. Create a greater level of awareness of global challenges and design constraints that include social, political, health and safety, environmental and sustainability issues;
3. Effect a shift in thinking towards that of holistic, systems approaches;
4. Effectively reach students of all learning styles;
5. Increase engineering students' valuation of related subject domains (science, math, communication);
6. Effect deeper learning in freshman-level science, math and communication courses;

Research question 2:

Is the TriAD curricular approach effective in retaining women and underrepresented groups in engineering programs?

That is, does it:

7. Create learning communities that strengthen students' resilience in difficult academic times;
8. Increase the retention rates of underrepresented individuals;
9. Increase the retention rates of engineering freshman;

Research question 3:

Are existing pre-college web-based math and science tutorials effective in increasing the success rate of underrepresented groups at college?

That is, does it:

10. Result in freshmen within these groups who are not required to take remedial math;
11. Result in fewer incidences of academic probation within these groups due to math and science courses;

Our TriAD approach draws upon eight best practices from education research

To accomplish our objectives, we have chosen to incorporate eight "best practices" of education within our TriAD approach. The eight best practices are depicted in Figure 5 and discussed below.

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;[21,22] subjects are often taught in such a way that makes them seem irrelevant to everyday life. **For our TriAD approach, we borrow from the principles of *service learning*, in which the learners are engaged in experiential learning that addresses human and community needs.**

   A number of researchers in engineering education have documented the benefits of service learning toward fostering desirable qualities within students. For example, engineering students involved in service learning demonstrate a stronger ethic of social and civic responsibility,[23] develop empathy for others,[24] demonstrate greater personal growth (maturity) and develop a broader appreciation of non-technical concerns and the impact of technology on society.[25]

We believe that providing a balanced degree of meaningful context will contribute to increased 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.[26] 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.[27] 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%).[28]

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.[29] Unsurprisingly, motivation strongly affects the amount of time one is willing to devote to learning,[30] and time is a critical element in learning a new subject.[31]

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.[32,33,34] 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.[35] 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.[36] **The type of integrated, activity-based design courses that we are proposing has been shown to be especially effective at retaining women and other underrepresented groups.**[37]

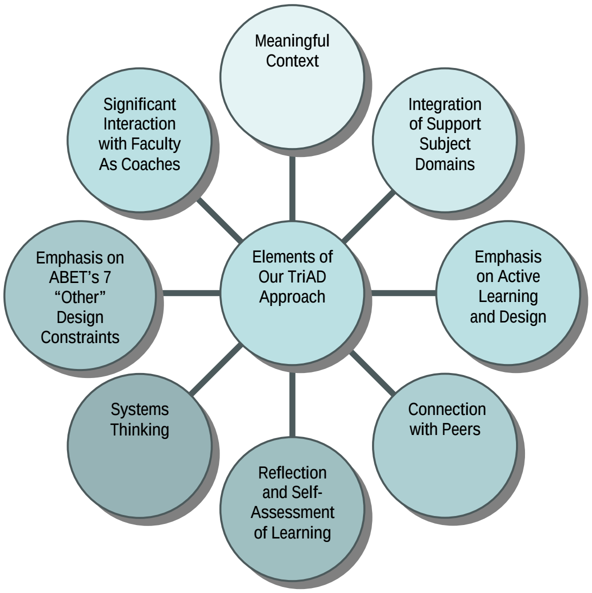

Figure 5. Eight "best practices" in our TriAD approach

A number of engineering programs have reaped the benefits of synergy in freshman integrated curricula. For example, members of the *Foundation Coalition* found that students in their integrated curriculum not only out-perform their peers in traditional curricula, they exhibit greater interest in learning beyond the required course material as well as a greater maturity and professionalism.[38] Olds and Miller demonstrated that students who participated in a freshman seminar that was designed to promote integration of the engineering support courses (science, humanities, and engineering courses) graduated at significantly higher rates compared to other engineering students.[39] Lengsfeld *et al.* integrated freshman engineering courses with English.[40] With only a one-week investment in the initial planning of the course integration, they have been able to see a noticeable increase in retention rate of the students. The level of integration has varied from cases where the investigators changed the syllabi to demonstrate clearer links between support courses and engineering courses, to situations where math, science and engineering were fused into one freshman experience.

The level of integration that we propose is somewhat different from what others have done. Rather than creating artificial "applications" to match the science and math curricula, we will draw upon the math and science that naturally occu[41]r in the particular design application. For example, the groundwater purification project will naturally contain Ohm's law, derivatives and integration, basic chemistry, exponential relationships, linear regression, logarithmic plotting, basic thermodynamics, communication skills and a number of other support topics. This will be the students' *first* exposure to applying many of these principles. Our research has shown that an integrated experience is valuable for deeper learning, but lacks full power if its integration is not practiced throughout the curriculum.[42]

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.[43] 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[44] 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[45] or Colbeck, Campbell and Bjorklund[46]) 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. (All PIs on the project have been utilizing active learning methods in their courses for several years. However, active learning by itself is not enough.)

   A fairly recent poll indicates that the top three work activities performed by engineers are 1) design (36%), 2) computer applications (31%); and 3) management (29%).[47] Active learning is particularly appropriate for design, as designing requires careful attention to the process of developing a solution, rather than a single, "correct" answer. When making decisions in the design process, an engineer is required to balance the inherent trade-offs. Unlike answering questions on a test, there isn't a "correct" solution. We have chosen to emphasize design at the freshman level because it motivates students by showing them more of what real engineering is about.[48]

   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 we are aware that the freshman version of design will be 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.[49] 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*[50] in our department. It is an atmosphere in which students help one another solve problems and encourage each other toward their goals. In fact, when asked what they like about our department, students often cite the "family" atmosphere, stating that it played a critical role in their survival as an engineering student. We have been successful in intentionally building and fostering learning communities through team assignments and homework groups. We will build on what we have found to be successful in the past. Also, we have teamed up with Cal Poly's Women's Engineering Program to provide a support network for freshman in the dorms (see letter of support in Supplemental Documents).

5. Reflection and Self-Assessment of Learning: Reflection is one of the essential components of *service learning*[51,52] 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.[53]

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.[54] Many have identified the need for this type of education in design.[55,56,57] We will **promote systems thinking** through repeatedly presenting the material as a system. A systems approach to design involves learning that complex systems cannot be optimized by simply optimizing individual subsystems; it requires an in-depth knowledge of how the subsystems interact with each other.[58] In the last couple of years, the PIs (LV, RS, KC) have been exploring ways to promote systems thinking. One method that we have been utilizing is an **emphasis on graphical depictions of events and patterns** as suggested by system dynamics practitioners.[59,60] We have not formally assessed whether this approach promotes more holistic thinking. This work would enable us to do so.

   While testing our methods, 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.

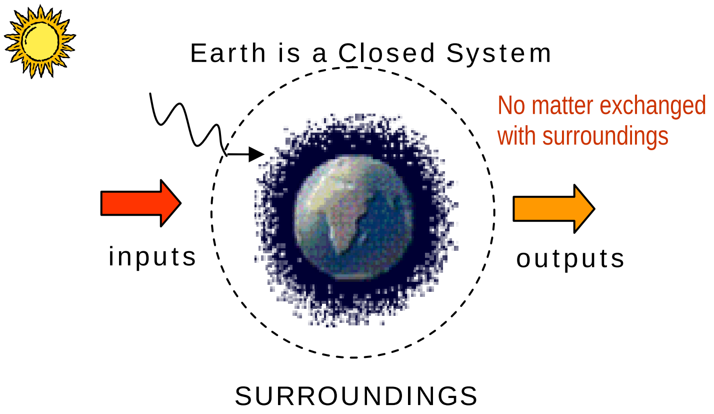

Figure 6. Earth is essentially a closed system. Energy can enter and exit, but no matter can enter or leave the system.

7. Emphasis on ABET's 7 "Other" Design Constraints: The Accreditation Board for Engineering and Technology (ABET) recently underscored the importance of the following eight criteria by making them more prominent in multiple places of the accreditation criteria: economic, environmental, health and safety, sustainability, social, political, ethical and manufacturability issues.[61] While programs often require a course in engineering economics, the seven other design constraints are often de-emphasized. Yet many experienced engineers, such as Gene Moriarty, recognize that these other constraints are *essential* to the design process.[62] 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, **TriAD** thinking. (Our faculty have developed working documents on the meaning of each of the design constraints and how we propose to integrate them into the curriculum. We have made these available to the public through our website www.mate.calpoly.edu/quest.)

   Designing for the triple bottom line naturally forces one to consider the design constraints emphasized in the ABET accreditation criteria: manufacturability, sustainability, health and safety, environment, ethics, politics, society and economics.

8. Significant Interaction with Faculty as Coaches: Faculty interaction and feedback play vital roles in whether engineering students gain skills.[63] 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.[64]

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