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Cultivating Sustainable Thinking in Engineering Students: Effective methods to inspire sustainable engineering solutions

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ABSTRACT

As sustainability gains global acceptance within the public consciousness, governments and voluntary trade organizations like the *International Organization for Standardization* underscore the imperative to balance the economic, environmental and social needs through their policies. Clearly, the changing rules of participation in the global economy are transforming the way that products and processes must be engineered. Will a new discipline of “sustainability engineering” emerge? Or, is it possible to restructure the approaches of existing engineering disciplines? We believe that the transition to sustainable solutions requires all engineering disciplines. In fact, many practicing engineers are unconsciously contributing to sustainability through their design solutions. Yet a new way of approaching the design process must be embedded within university education for engineers to have the systemic thinking and global awareness needed for the rapid conversion to sustainable economies. In this paper, we discuss a variety of pedagogical techniques that we have utilized to promote the qualities that are required for developing sustainable solutions. They include service learning, promoting global awareness and vision, providing a perspective on the design constraints, and utilizing tools to evaluate and assess a design’s impact. These topics can be embedded easily within the “normal” engineering course material. We will present our techniques, learning objectives and data on how these classroom methods have influenced engineering students’ thinking.

Introduction

The need for economies based on sustainable development has gained critical mass in the global arena, underscored by the *United Nations’* declaration of 2005-2014 as the decade of education for sustainable development.[1] The *International Organization for Standardization’s* (ISO) creation of 14 000—business standards for environmental practices—and 19 000—business standards for socially responsible practices--[2] is among the many other signs of a shift to sustainability.

The challenge that we face as engineering educators is how to prepare students to function in this new design environment. Many educators, when faced with the dilemma of “adding” material to the engineering curriculum, reasonably ask, “What should be taken out in order to make room for this new material?” We propose that educating engineering students for sustainable development requires more of a shift in mindset rather than replacing large elements of what is already done in the curriculum; it requires a small change in what we present and a larger change in *how* we present it. We still must ensure that students are able to solve engineering challenges.

However, as the United States' *Accreditation Board on Engineering and Technology* (ABET) has recognized in their 2004 criteria revision, students must also possess the ability to think systemically; their solution must consider societal, ethical, health and safety, environmental, political, and sustainability issues along with the traditional considerations of manufacturability and economic issues.[3]

We believe that the transition to sustainable development requires what we call *sustainable thinking*, a new way of approaching challenges. It involves four qualities: An ethic of social responsibility, vision for a sustainable future, systems perspectives and resource consciousness. This paper describes methods that can be used in the classroom to promote the development of the engineer who possesses the attributes for sustainable thinking and we also present data that indicate their effectiveness in shifting students' mindset.

Fostering the ethic of social responsibility

The United States National Society of Professional Engineer's statement of ethics is similar to many other professional societies' in that it confirms that the purpose of the profession is to serve humanity[4]. It states that "…I dedicate my professional knowledge and skill to the advancement and betterment of human welfare." In essence, social responsibility (i.e., the ability to act on behalf of the greater good) is as much a core element of the engineering profession as is the ability to apply technical knowledge. However, developing the ethic of social responsibility is a process that is deeply grounded in experiences outside the traditional classroom: local culture, exposure to other cultures, family and societal values, religious and moral beliefs. Although these experiences are beyond the scope of a traditional engineering curriculum, there are activities that fit well within curricula and also cultivate this ethic.

Over the past two years we have been experimenting with exercises that are designed to promote the students' awareness of social responsibility. We did this in two formats with two consecutive freshmen cohorts: A lecture format (1-hour per week for 20 weeks) and a laboratory format (3-hours per week for 30 weeks). The 2003 cohort was not significantly different than the 2004 cohort in terms of their performance on standardized tests and other admission criteria. However, the 2003 cohort was 20% female (7/35) whereas the 2004 cohort was ~8% female (3/37). We utilized *attitude surveys* at strategic points within the 2004 cohort's experience. These surveys were designed to detect a change in attitude over the course of the experience. Unfortunately, we did not test the 2003 cohort at comparable points in the experience. Figure 1 depicts the treatments of both cohorts. Note that the 2003 cohort did not take the attitude survey until the winter quarter of their sophomore year.

Both cohorts were sent textbooks in the summer before entering Cal Poly and invited to read them before coming. The 2003 cohort was sent *The Engineering Student Survival Guide*, by K. Donaldson,[5] whereas the 2004 cohort was sent *Biomimicry: Innovation Inspired by Nature*, by J. Benyus.[6] The *Guide* is a very practical handbook for freshmen engineering students that explores such topics as note-taking techniques, studying for quizzes, and balancing studying with play. In contrast, *Biomimicry* is a visionary look into technological design after nature's highly efficient models. It is geared toward a more sophisticated audience and poses a number of provocative ideas. Additionally, both cohorts were exposed to the engineering ethics creed and required to complete reflection assignments (i.e., assignments in which the student is asked to "reflect" on their point of view) involving ethics and topics within their textbook. We chose *Biomimicry* to set a tone of higher expectations of social responsibility. The 2004 cohort engaged in weekly discussion groups on a chapter of *Biomimicry*, lead by an upperclassman during spring quarter.

The 2004 cohort also participated in a 2-quarter project to design a water purification system for a local family who uses ground water as their water source (versus water regulated and supplied by local governments). The class was broken into formal teams of four students each and given a unique family client with unique ground water challenges. One of the constraints of the design was that their system could use only renewable energy to function. That is, their design could not demand additional non-renewable energy from the site. The team experience began with a visit to our local landfill to consider issues of run-off and ground water. Then each individual team met the clients at their site, interviewed them about their needs and took water samples. The teams completed the design work during the lab periods under faculty guidance. This included defining the problem, articulating functional requirements for the system and a peer-juried design review. Each team was given a great deal of freedom to interact directly with their clients. At the end of the year, they installed the system, tested the water and provided a set of operating documents to the client.

Table I summarizes the differences in the exercises between the 2003 and 2004 cohorts. The goal of using the activities listed in Table I was to foster the ethic of social responsibility. The reflection questions took the form of questions in which students had to evaluate their perspective such as *Why did you choose to major in engineering? What do you plan to contribute to society during your career? What should be sustained for future generations? What can you, as an engineer, do to enable the transition toward renewable forms of energy?*

To measure whether students were at least aware of the idea that the role of the engineer is to apply their knowledge in service to society, we asked the following question: *What do you see as the role of the engineer in society?* We rated the responses with either 0 (displays no recognition that the role of the engineer is one of service to society for its welfare) or 1 (shows a recognition that the role of the engineer is one of service to society for its welfare). For examples, answers such as the verbatim responses, "To make new and improve old" or "We make things happen" received a 0. Answers such as "I think the role in engineering, in society is to improve the betterment of people living on earth or elsewhere" received a "1".

The initial responses of the 2004 cohort (taken on their first day of their class) show that serving humanity through their profession was not in the scope of their thinking; 23 out of 28 students received a 0 rating. We do not have initial responses for the 2003 cohort, although because of their academic and demographic similarity, we expect them to be similar. The 2004 cohort data was also analyzed through a paired-t test where the rating of their response after experiencing the course was subtracted from the rating of their initial response. The results indicate that there is a statistically significant change toward a greater recognition of an engineer's social responsibility (μ_i = .185 ± 0.076; μ_f = .778 ± 0.082; $\mu_f > \mu_i$ with P-Value = 0.000 for 95% confidence level, where μ_i is the initial mean and μ_f is the final mean.)

Table II shows a tally of the final cohort data for comparison. As shown, the 2003 cohort data from the survey administered during their sophomore year, showed that there was no significant difference in the proportion of students who received a “1” rating on their final answers compared to the 2004 cohort data. Because both cohorts were similar in their educational demographics, one could argue that their initial responses would have been similar if they were measured. That is, it is likely that prior to the 2003 cohort’s freshman experience, the majority of the students would have received a rating of 0 on their response.

We also evaluated the quality of the response for “sophistication” of the answers. The ratings were 0 (same as above), 1 (same as above) and 2 (a greater level of thought). An example of an answer that scored a “2” in this second rating is *An engineer’s role is to advance the development of society and technology, improve people’s lives, insure the safety of the public, and protect the environment.* We emphasize that the cohorts were not significantly different in terms of their academic metrics when accepted to Cal Poly. However, as shown in Figure 2, although the proportions receiving “0” were similar (7 out of 19 for 2004 compared to 7 out of 23 for 2003)there were a greater proportion of “2” responses in the 2004 cohort (6 out of 19 for 2004 compared to 2 out of 23 for 2003). The 2004 cohort had the additional experiences of serving a client and group discussions of *Biomimicry*. Although it is difficult to point to any one element, it is clear that the 2004 cohort had a greater sophistication in their view of engineer’s responsibility to society.

By introduction to the ethics creed, students begin to see themselves as part of the larger organism that we call *society*. The reflection exercises force the students to examine societal challenges in relation to themselves, making the issues personally relevant. The fact that the same proportion of the 2003 cohort demonstrated an awareness of the social responsibility aspect of the engineering profession may simply be coincidental. Their sophomore course instructor indicated that she gave a recent assignment related so social responsibility before the attitude survey was administered.

The project with real clients was meant to give a human-touch to their engineering activities. Indeed, one of several unexpected results was the frustration the students experienced in working with real clients who had a different sense of urgency. One client changed their minds mid-way through the project, forcing the group back to the drawing board. Another unexpected result was that one group of students was actually less motivated to work on their project because their client was so clearly affluent. However, for the other seven groups, students universally reported that they were more motivated to do a good job because the client needed their help. This supports the results in literature about *service learning*; it is best when done for a client who is less fortunate. 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,[7] develop empathy for others,[8] demonstrate greater personal growth (maturity) and develop a broader appreciation of non-technical concerns and the impact of technology on society.[9]

Creating a vision for a sustainable future

Having a vision of a new and better future (in our view, one that is based on a sustainable practices), is critical; it is hard to get somewhere if you do not know where you are going. It is also necessary to have an understanding of where we are as a species and why it is that we need to embrace sustainable development. We approached the idea of developing vision by coupling an awareness of global issues with inspirational examples of design. For example, we would bring in current news articles on global issues such as global climate change, global energy demands versus projected supplies, and environmental injustice (i.e., shipping pollutants to areas of the world where there is greater poverty and greater illiteracy). These articles would be coupled with reflection assignments. We showed two inspirational documentaries: *The Next Industrial Revolution*,[10] documenting the work of W. McDonough and M. Braungart of *Cradle-to-Cradle* fame;[11] and *PowerShift: Energy and Sustainability.*[12] These were also coupled with reflection assignments. The 2003 cohort received fewer reflection assignments, fewer articles and did not see the videos. These elements were added to the 2004 cohort courses.

To measure shifts in awareness, we used the attitude survey mentioned earlier, administered on the same points in the experience. One of the questions aimed at detecting awareness of global issues was *What do you believe will be the greatest challenges to the engineering profession over the next 30 years? (List as many as you can think of.)* The responses were scored as 0 (no recognition of global issues), 1 (a slight recognition, perhaps one issue recognized) and 2 (significant recognition-two or more global issues listed). We made the distinction between *global* issues and *local* issues. For example, the verbatim response “outsourcing of engineering jobs” received a 0, as it is a local (U.S.) issue. A response listing one issue, such as “global warming” or “developing renewable energy technology” received a 1.

For the 2004 cohort, the mean score for their response on the first day of the course was μ_i = .158 ± 0.086. The mean score for the response at the end of the freshman course sequence was μ_f = 1.37 ± 0.16. A paired t-test of the data indicated that $\mu_f > \mu_i$ with probability of error of 0.000 (P-value), using a 95% confidence level. In other words, there was a statistically significant increase in their awareness of global issues after the course sequence.

As can be seen in Figure 3, fewer respondents from the 2004 cohort received a rating of 0 for their response (2 out of 19 versus 7 out of 23 for the 2003 cohort). Also, a greater number of responses from the 2004 cohort were rated as a 2 (11 out of 19 versus 9 out of 23 for the 2003 cohort). A two-sample t-test of the mean ratings for these data sets shows that the mean of the 2004 cohort is larger than that of the 2003 cohort using a 95% upper bound for the difference at a confidence level of p=0.056 (μ_{2003} = 1.087 ± 0.18; μ_{2004} = 1.474 ± 0.16). This indicates, acknowledging the 5.6% probability of being incorrect, that the 2004 cohort demonstrated a greater awareness of global issues compared to the 2003 cohort.

Developing systems perspectives

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.[13] Many have identified the need for this type of education in design.[14,15,16] We promoted systems thinking through repeatedly presenting ideas as “systems,” using sketches of flow diagrams to show relationships of the inputs, outputs, system and surroundings. For example, when we spoke about designing the system in our freshman course, we presented a graphic and discussed the entire life cycle, based on the convention proposed by the United States Environmental Protection Agency[17]. This convention, shown in Figure 4, reminds students that designing a product involves far more extractions from the environment and emissions to the environment than simply the manufacturing process.

Students' shift in mindset was immediately visible after introducing the simple idea of the earth being a closed system as depicted in Figure 5. Early in the Fall 2003, the students were given predictive data on global climate change 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.

Promoting resource consciousness

According to Wackernagel *et al*., the global population is currently consuming natural resources at a rate of 120% of what the earth can regenerate.[18] David 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.[19] Although some of the scientific understanding finds its way into mainstream acceptance through books like *Biomimicry*, it is difficult for students (and others within the United States) to believe that we could be facing a shortage of resources. However, due to the relatively high cost of energy in California (compared to other parts of the United States), students are willing to accept the idea that we could face an oil crisis in their lifetimes.

One of the ways in which we promoted resource consciousness is through the tool of "environmental footprinting."[20] We used a worksheet version but an electronic version is available on-line. This tool is a means of converting human activities to an equivalent area of bioproductive land that is consumed by the activity. Because the earth has a fixed amount of bioproductive land, the students can start to see their lifestyles in light of how much of the earth's bioproductive land they are consuming. We used this method with the 2003 cohort. Unexpectedly, the students' footprints came out artificially low due to living in the dormitories. Their energy usage is highly skewed to lower values because they did not enter any information from heating/cooling their living space or their water usage. If using the footprint tool, ensure that the footprint is adjusted upward to reflect dormitory living. We did not use the footprinting tool for the 2004 cohort.

One of the metrics used for determining students' resource consciousness is the number of students who mention resource limitations in their response to the question *What do you believe will be the greatest challenges to the engineering profession over the next 30 years? (List as many as you can think of.)* For the 2004 cohort, 15 out of 19 students demonstrated a resource consciousness in their end-of-course responses. Only 11 out of 23 of the 2003 cohort did so in theirs. Additionally, for the 2004 cohort, there was a statistically significant transition from a lack of resource consciousness as a critical issue (i.e., 17 out of the 19 gave initial responses that were rated “0”) to an awareness. The lower proportion of students in the 2003 cohort could be due to the skewed environmental footprinting activity. However, we suspect that the combination of activities in the 2004 cohort made them more conscious of the limits on resources.

Conclusions

We believe that the shift to sustainable ways of living will require a fundamental shift in mindsets. We have integrated activities into our engineering courses that promote what we call *sustainability thinking*. These activities were designed to develop four qualities in the students: an ethic of social responsibility, a vision for a sustainable future, systems perspectives and resource consciousness. The activities include those that are small in scope—such as presenting the idea that the earth is a closed thermodynamic system, or assigning reflection questions—those that are medium in scope—such as conducting reading groups—to those that large in scope—such as a 20-week design project in service to a local family. The data from attitude surveys of student cohorts indicate that students’ understanding has shifted in at least three important ways, 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 promising.

Figure 1. Shading indicates when the cohort was in class. Note that the 2003 cohort was not given the attitude survey until the winter quarter of their sophomore year, nine months after their course ended.

Quarter:	*Summer*	*Fall*	*Winter*	*Spring*
2003 Cohort	In class (1 hr/wk):	9/2003	1/2004	
	▲*Sent text:* Engineer's Survival Guide			
			▼*2003 Cohort final survey date*	
2004 Cohort	In lab (3 hr/wk):	9/2004	1/2005	3/2005
	▲*2004 Cohort initial survey*		*mid-course survey*▲	*final survey*▲
	▲*Sent text:* Biomimicry			

Table I. Summary of experiences to promote social responsibility

2003 Cohort	2004 Cohort
1. Introduction to the engineering ethics creed 2. Reflection assignment on the role of the engineer in society 3. Reading one chapter in *The Engineering Student Survival Guide* geared toward ethics in engineering	1. Introduction to the engineering ethics creed 2. Reflection assignment on the role of the engineer in society 3. Reading the book *Biomimicry* 4. Visit to landfill to see impact of human activity on ground water 5. 20-week long project in service to a local family on ground water 6. Other reflection assignments
Learning Objective: *Imbue students with the engineering profession's social responsibility to better human welfare.*	

Table II. Tally of response ratings for the question, "What do you see as the role of engineering in society?"

Cohort	number of 0 responses	number of 1 responses	Total number of students
2003	6	16	22
2004	4	15	19

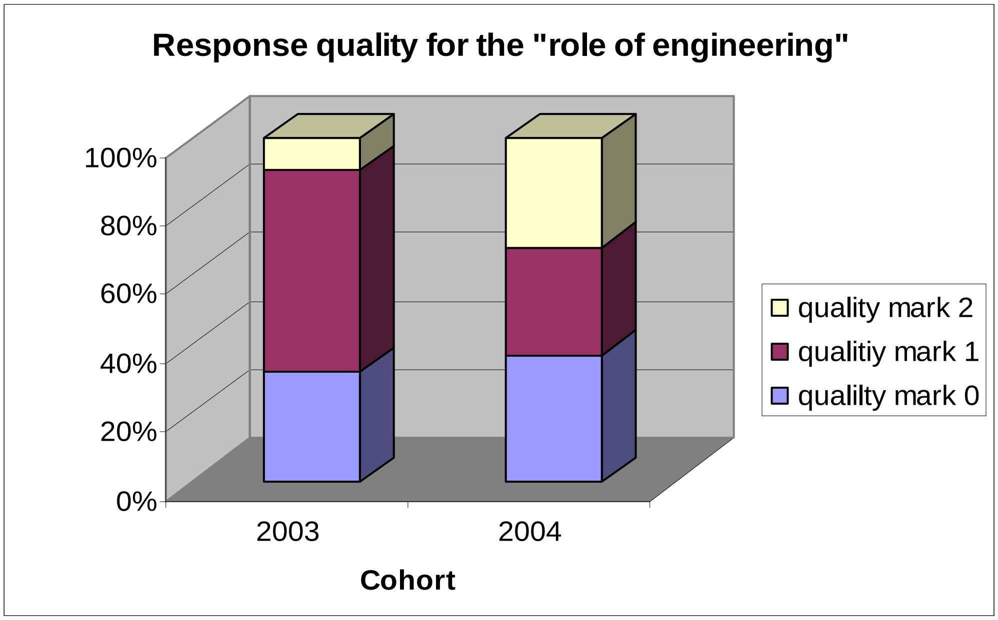

Figure 2. Distribution of students' response quality rating for the question "What do you see as the role of engineering in society?" The 2004 cohort demonstrated a greater overall sophistication in their answers.

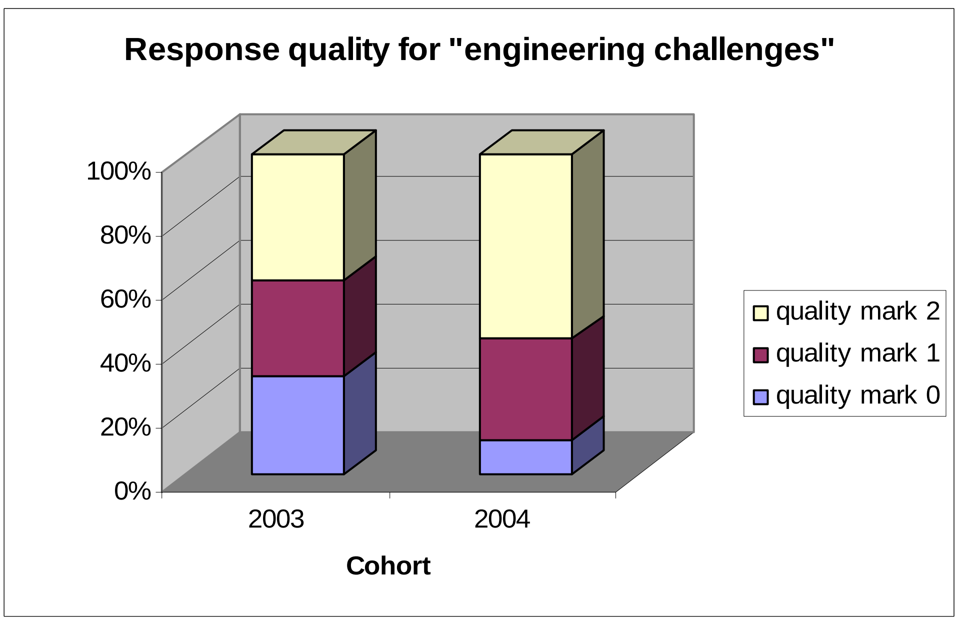

Figure 3. Distribution of students' response quality rating for the question "What do you believe will be the greatest challenges to the engineering profession over the next 30 years?" The 2004 cohort demonstrated a greater overall awareness of global issues in their answers and a greater global awareness.

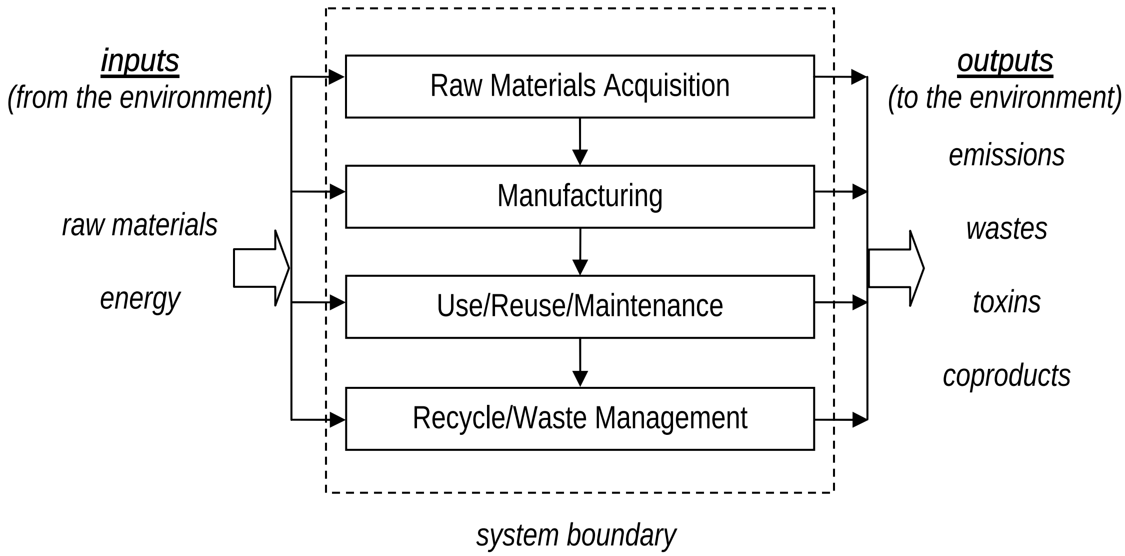

Figure 4. Life cycle stages. Adapted from reference 17.

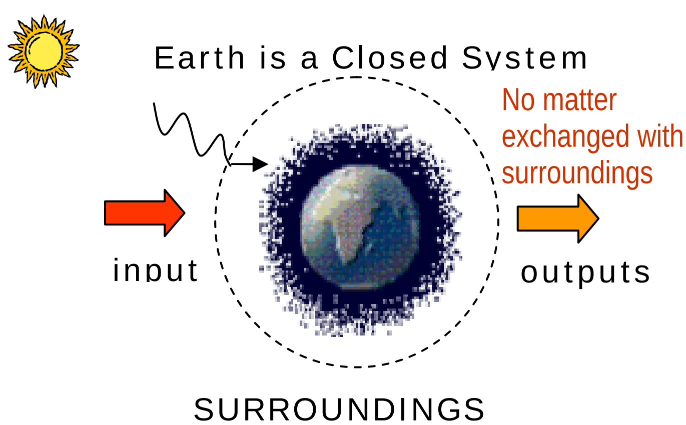

Figure 5. Presenting the earth as a closed system enables students to understand the connection between human activity and global climate change.

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[19] Goodstein, David, *Out of Gas: The End of the Age of Oil* (New York: W.W. Norton and Company, 2004) 128.
[20] For an introduction to *Ecological Footprinting*, go to www.redefiningprogress.org. The site also contains self-tests for individuals to determine their own ecological footprint.