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From Beginning to End: How Engineering Students Think and Talk About Sustainability Across the Life Cycle*

DEBORAH KILGORE, ANDREW JOCUNS, KEN YASUHARA and CYNTHIA J. ATMAN
Center for Engineering Learning and Teaching, University of Washington, Box 352183, Seattle, WA 98195-2180, USA. E-mail: kilgored@u.washington.edu. jocunsa@u.washington.edu. yasuhara@u.washington.edu. atman@u.washington.edu.

In this mixed-methods longitudinal study, 64 engineering students participated in a 15-minute lab-based engineering design task toward the end of their second and fourth years. Fifteen of those students also participated in open-ended interviews in their senior year, in which they were asked about their college experiences and conceptions of sustainable development. Analysis of these data reveal that while the students often talked about sustainable development in terms of limited resources and the life cycle of engineered products, relatively few considered the life cycle when actually engaged in engineering design. An in-depth examination of four students' educational experiences, narratives about sustainable development, and performance on the engineering task suggested implications for engineering education. Making sustainable development explicit in engineering classrooms and facilitating the development of self-directed learning skills in engineering students should improve students' abilities to develop knowledge about sustainable development and transfer such knowledge to new engineering contexts.

Keywords: design; sustainability; life cycle analysis; mixed methods research; undergraduates

1. INTRODUCTION

SUSTAINABLE ENGINEERING DESIGN requires not only the technical skills necessary to engineer solutions, but a broad vision of and sense of responsibility for the impacts that engineered solutions have on people and societies [1, 2]. ABET accreditation standards speak to this need by calling for engineering programs to provide students 'the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental and social context' [3]. Furthermore, ABET aspires for students to develop the 'ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability' [3].

One way of introducing sustainability into engineering design is through *life cycle analysis* [1, 4]. An engineering solution's life cycle includes all of the inter-related stages of its existence, from design, to implementation, to operations and maintenance, and, ultimately, disposal. A life cycle analysis facilitates comprehensive decision-making along many important dimensions, such as environmental impact, cost, resource requirements, manufacturability, serviceability and social impact. Additionally, considering an engineered solution's complete life cycle can reveal its relationships with other processes and systems, thus situating an engineering effort in larger contexts [4] as advocated by ABET. For instance, the design of an automobile tire might be informed by the target market's product safety regulations, material supply and product distribution chains, and car ownership rates and driving habits. By structuring an examination of the designed artifact across time, life cycle can facilitate these broad contextual considerations, *e.g.*, governmental, business, and cultural, respectively, in this case.

In *Educating the Engineer of 2020*, the NAE recommends 'student-centered education' as one cornerstone of engineering education reform [5]. Making education student-centered involves recognition that students are principle actors in the learning process, and teaching approaches should be geared toward reaching students with different learning preferences, histories, and perspectives. Therefore, in considering how sustainability concepts may be incorporated in engineering education, we believe a good place to begin is with students' current conceptions of and attitudes toward sustainability and sustainable development.

In this paper, we present a mixed-methods study of undergraduate engineering students talking about sustainable development and considering sustainability concepts across the life cycle during engineering problem solving. We conclude with an in-depth examination of the college experiences of four students, to see where their preparation for sustainable engineering, if any, came from. Students' conceptions of sustainable development,

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performance in engineering design with respect to life cycle analysis, and educational experiences related to sustainability inform our recommendations for incorporating sustainability in engineering education.

2. METHODOLOGY

The Academic Pathways Study (APS) is a multi-institution, mixed-methods, longitudinal study which examines engineering students' learning and development as they move into, through, and beyond their undergraduate institutions [6, 7]. It is part of the Center for the Advancement of Engineering Education (CAEE), an NSF-funded higher education Center for Learning and Teaching. The APS uses a concurrent triangulation mixed-methods design, in which both qualitative and quantitative methods are employed to collect and analyze data. The integration of results occurs during the interpretation phase [8]. Details of the APS research design is documented elsewhere (see, *e.g.*, [6, 7]).

The present study examines how students think and talk about sustainable development, as well as the extent to which they consider the life cycle while engaged in engineering design. Sixty-four students across four institutions completed an engineering design task in their second and fourth years. Fifteen of those students at one of the institutions, referred to here as Large Public University (LPU), participated in a semi-structured, qualitative interview in their senior year, in which they were asked to talk about sustainable development and other concepts related to engineering. Questions about sustainable development were posed to these students shortly after they had completed the engineering design task.

Analysis of the students' conceptions of sustainable development was accomplished in tandem with coding of their written answers to the engineering design task. In the following sections, we will describe findings from our analyses. First, we will describe how students talked about sustainability and sustainable development in terms of *limited resources* and *life cycle*. Second, we will show the extent to which students considered life cycle while solving an engineering design problem. We will close by examining the learning experiences of four students who described their conceptions of sustainable development, to better understand the link between learning and applying the concept of sustainability and the implications for engineering education.

3. FINDINGS

3.1 Students' conceptions of sustainable development

We were interested to learn the degree to which the aspirations of policy makers had permeated the students' engineering education experience. Therefore, we asked students to respond to a quote from the *Engineer of 2020*: 'It is our aspiration that engineers will continue to be leaders in the movement toward use of wise, informed, and economical sustainable development' [5]. We then asked students the following questions: (1) What do you think they mean by 'sustainable development?' (2) To what extent has your education provided knowledge about sustainable development? (3) How well prepared do you feel to contribute to sustainable development?

Two overlapping themes dominated students' responses to questions about sustainable development, and we coded them accordingly: *limited resources* and *life cycle*. We assigned a code of 'limited resources' to a response when the participant offered a comprehension of sustainable development in which the world's natural resources are being over-mined, over-used, and as such are in danger of depletion. We assigned a code of 'life cycle' to a response in which the participant referred in some way to a stage of the life cycle of an engineered product—for example, the design process, construction, maintenance, and disposal. We considered all 15 students' responses in terms of these categories. The discussion following reflects the entire range of responses.

In the following sections, we interpret *limited resources* and *life cycle* as narratives or stories that students tell about sustainable development. With this analytic lens, we acknowledge that the ways students talk about sustainable development reflect the social, cultural, and educational contexts in which they make meaning of their lives [9].

3.2 Limited resources

In their explanations of sustainable development, eight of the 15 students discussed the Earth's limited resources. These responses ranged in richness and specificity, from rather vague responses to more sophisticated ones that included specific examples (*e.g.*, reducing reliance on fossil fuels) and/or were tied more explicitly to students' experiences in engineering education.

Austin, a mechanical engineering major, articulated little understanding of sustainable development, other than 'something that isn't . . . going to use up some resources in a short period of time . . .' Samantha also explained sustainable development in terms of limited resources. She referred to 'green' energy resources but appeared somewhat unsure of her explanation, prefacing her remarks with 'I guess' and 'I don't know.'

> I guess like it makes me think of the green buildings that can be sustained without too much energy input . . . So they're like—I don't know if any of these sound sustainable, but like they're able to continue operation using energy resources that they're—green energy resources, so like if they grew plants on the top of their building or something to do—to somehow reduce like the heating cost or

> something . . .Um, I guess it's just all in—a lot in the materials that they use to build, so there's less heat escape or like, um—or like the solar panels or something.

Samantha was more specific than Austin, referring to both energy conservation and an example of a renewable energy source (solar) with respect to 'green' building. She also mentioned that she became acquainted with green energy concepts through an architecture course she took and not from coursework in her major, bioengineering.

Drew, a chemical engineering major, was passionate in his opinion about people's responsibility to conserve the Earth's resources.

> Well, sustainable, we do not live a—in a sustainable culture, and now we're just milking this oil, the cheap energy that's coming out of the ground, and it's not sustainable, because it's going to run out eventually, or at least become—get to the point where it's too expensive—it's too expensive. And when I think of sustainable development, it's something that won't run out, won't become—I don't want to say won't become obsolete, because eventually it will become obsolete, but it won't—man, I don't know where to go with that.

Drew connected human action and culture—'milking this oil'—to his understanding of sustainability. Ethan took a similar stance, referring to the fact that humans have already 'paved over' the environment and that it is almost too late to save it. 'We talk about saving the environment, but if people would actually research what the environment looked like 150 or 200 years ago, they'd probably decide it's a little too late to save it. It is gone.'

Both Drew and Ethan expressed passion for sustainability and situated sustainable development in human history, culture, and economic systems, but Ethan went as far as to connect this larger view with his motivation to become an engineer. 'I'm interested in energy systems, and, I guess, I feel like there's so much work to be done switching people over from easy, cheap, money-making solutions to something that people can use hundreds or thousands of years into the future.' Ethan's explanation of sustainable development stresses limited resources but also takes a longer view, suggesting that limited resources are part of a larger puzzle: the life cycle of an engineered solution. We will describe this life cycle stance toward sustainable development in the next section.

Jesse's response offered two more components to the limited resources stance, as he suggested that it is not just humans who are to blame for 'unsustainable cultures' but also that engineers are responsible for fixing the problems. Jesse is unique among our respondents in identifying the importance of sustaining intellectual resources. A mechanical engineering major, he pointed out that engineers cannot simply throw technology at a problem, but rather must ensure that people know how to use and maintain engineered products throughout their useful life.

> Economic, sustainable development . . . it's kind of like helping people raise their own standard of living, and I mean it's kind of like the . . . 'give a man a fish, teach him how to fish' difference, so it's kind of like giving people the—not giving people tools—like describing through teaching people the tools to like, you know, bring their own level of economic development up, and instead of just like flooding in new technology or money, like just doing it in a smart and more effective way . . .engineers are responsible for increasing the standard of living for all levels, for all people . . .

In sum, students' conceptions of sustainability as an issue of limited resources ranged from very vague to rather promising in terms of demonstrating advanced knowledge, skills and attitudes about sustainability and sustainable development. Their narratives suggested varying degrees of sophistication in their conceptions of sustainable development as a question of limited resources. Some students gave specific examples to illustrate the concept of limited resources. Others situated their discussion of limited resources within larger economic, environmental, global, and/or social contexts. Jesse connected his discussion of limited resources with the engineering profession, specifying an ethical principle that engineers should follow in their work.

3.3 Life cycle

Responses to the sustainable development question that maintained a stance towards the future of the product, not just the end of the design process, we refer to as *life cycle* stances. Students took sustainable development in the life cycle sense to refer to the lifetime of a product, by taking into account materials and design features that will have positive effects upon the maintenance and life of the product, as well as the world context in which the product will be used. In discussing sustainable development in terms of the life cycle, Emily focused on efficiency, 'Well, it just—it means that, um, you don't have to start over every time you're doing something. It means that with maintenance and stuff, that our society can keep—keep running, and you don't have to just wipe it out and start over again all the time.' Like Emily, Justin understood sustainable development and the life cycle to be, at least in part, for the purpose of efficiency and not 'reinventing the wheel.' This understanding of the life cycle of design reflects one of the dominant images of engineering that were noticed in previous analyses of undergraduate majors, who realized that they would not be constantly designing new products but extending or improving designs that are already in existence [10].

Michael considered the engineering problem solving process itself as the object of sustainable development. Michael contrasted a process that is 'solution oriented' to a more 'sustainable sort . . . where when you develop the solution you think about the long-term impacts and not just solving the problem in short-term.' Taking the longer view, engineers would be pragmatic, 'probably developing solutions that are useful instead of just impressive.'

For some students, in addition to considering the larger context of an engineering design problem, it also was important to consider life cycle within the more immediate context. For example, Amanda said, '[Y]ou want to move away from depletable resources and move towards renewable resources, things that won't pollute the environment and [are] economically sustainable. You have to sort of cater to a region, like it wouldn't make sense to use solar panels in Washington, or at least in Seattle or something.' Justin considered another kind of immediate context—that presented by his major in computer science and engineering—as he explained his understanding of life cycle assessment and sustainability.

> The closest thing [sustainable development] would be related to, would be reusing old code, which means someone has probably already written what you want to do, so—and they've probably also packaged it into a library that you can freely use, which means you don't have to rewrite everything. You just have to plug in their stuff and start using it, and that's sustainable because if you're not reinventing the wheel every time, you actually—you don't discover the same bugs, you don't waste the same development time . . . Like if you have the domain knowledge, you know these things exist. You know you don't have to reinvent that wheel.

Kara, a mechanical engineering major, gave a detailed explanation of how sustainable development involves 'our ability to analyze the life cycle of a product and how from beginning to end it—it affects society.'

> So it's not just how much it costs to produce but how much it costs to get rid of it when you're through with it, and how we can design in the first place to make it more usable when it's through or to allow it to be used for energy to produce more products or to be recycled . . . and just like in this whole 'let's reduce carbon emissions' issue, looking at, again, the life cycle of the solutions and, you know, is it more effective to burn paper, to make new paper out of trees rather than trying to recycle it, is it more energy efficient . . . So in terms of energy and products and waste, and even independence in, for instance, housing design, you know, coming up with new materials and new methods of production that allow development to be more independent and self-sufficient and fair use of energy and so forth . . . Um, understanding what their priorities are and how your solution will affect them in kind of a life-cycle sort of a way from beginning to end will help improve the engineering of the future.

Kara's life cycle stance towards sustainable development was more complex than a simple projection of a designed product into the future, and contains several qualities that signify a relatively sophisticated understanding of sustainable development and more specifically, life cycle analysis. First, Kara situated sustainable development in a societal context. Second, Kara offered a specific example of decision-making using life cycle analysis. Third, Kara connected sustainable development to the design work that engineers do, introducing the human element in the latter part of her response by referring to how engineers must take into account users and their priorities.

Though the above narratives varied in detail and richness, they tended to be more connected to the engineering design process than the *limited resources* narratives. Students' explanations of sustainable development in terms of life cycle analysis tended to include engineering design concepts and the design process itself. These concepts included efficient design processes, more pragmatic design decisions for the long run, and gathering information about users' priorities. It is useful to note that the questions about sustainable development posed during the interview occurred after students had engaged in a 15-minute engineering design task. Perhaps students who connected sustainable development to engineering design may have been influenced by the order of questions. However, many students did not connect the two, which suggests that the order of activities in the interview was not a substantial factor in shaping students' responses. In the next section, we discuss how students addressed issues of sustainability, and more specifically life cycle, while doing that engineering design task.

3.4 Students' application of sustainable development concepts in engineering design

To complement our interview-based understanding of how engineering students talk about sustainable development, we also analyzed data generated from students engaged in an engineering design task. Students were presented with the same design task in their second and fourth years of undergraduate study (2004–2005 and 2006–2007 academic years). The 15 interview participants at Large Public University who are the main focus of this paper were among the longitudinal sample of 64 students across the four institutions for whom we have paired second- and fourth-year design task data. LPU was overrepresented in the sample, with 41% of participants. The other pseudonymous institutions were Technical Public Institution, Urban Private University, and Suburban Private University, with 19%, 16%, and 25% of participants, respectively. Women were oversampled and represented just under half of the sample.

We collected written responses to four open-ended questions about designing a way for pedestrians to cross a busy street intersection [11]. The street crossing design task was administered on paper with a 15-minute time limit and opened with a brief description of the problem scenario:

> As an engineer, you have been asked to solve a problem on the State University campus. Just like campuses across the country, the State University campus is often overcrowded with pedestrians cross-

> ing the streets. One busy intersection on campus is the crossing of Fifth Ave. in front of the bookstore. Dangers at this intersection include heavy traffic and busses which run against the general traffic flow (see diagram below). The University would like to design a cost effective method for students to cross Fifth Ave. which would reduce the possibility of accidents at this intersection. You have been assigned to design a solution to this problem for presentation to the University Traffic Committee.

The description was accompanied by a diagram of the intersection and was followed by four, open-ended questions, each intended to focus on a specific design activity:

(1) What is the problem as you see it?
(2) List potential solution(s) for this problem.
(3) From your list in Question 2, choose the potential solution you think is best and provide a detailed evaluation of your solution.
(4) What kinds of additional information would help you solve this problem?

In this paper, we focus on an analysis of responses to Questions (2) and (3) that examines the extent to which students considered sustainability when evaluating potential solutions in the street crossing design task. (Although only Question (3) asks for solution evaluation, many students began evaluating potential solutions while listing them in their Question (2) responses, so we decided to include both in this analysis.) Responses were coded according to a scheme inspired by life cycle analysis, a tool commonly used to assess an artifact or system's environmental, economic, and social impact at each stage of its lifetime. Our coding scheme recognizes four stages of a designed solution's lifetime, listed in chronological order: CURRENT STATE, DESIGN/CONSTRUCTION, SOLUTION IN PLACE, and MAINTENANCE/DISPOSAL. A brief description of each code is given in Table 1. Coding a participant's responses involved a yes/no judgment for each stage, depending on whether the responses included evidence of consideration of the stage. A detailed set of coding guidelines was refined until two researchers were able to independently code with agreement for at least 80% of participants. Disagreements were negotiated to consensus. The findings reflect how broadly students considered life cycle when completing the street crossing design task.

Since Questions (2) and (3) both explicitly requested that potential solutions be listed and evaluated, all participants' responses ended up being coded 'yes' for the SOLUTION IN PLACE code. The code is described above for the sake of completeness but was not analyzed. In contrast, we expected relatively few students to consider DESIGN/CONSTRUCTION and MAINTENANCE/DISPOSAL in describing and evaluating potential solutions, at least in their second year. We hoped that this might change after two years of engineering study.

Indeed, as second-year undergraduates, only about a quarter of the 64-student sample considered each of CURRENT STATE and DESIGN/CONSTRUCTION in their responses, and even fewer considered MAINTENANCE/DISPOSAL. Most of the response text described solutions in their fully constructed state and did not discuss the duration, complexity, or resource requirements of the design or construction stages in the life cycle. With respect to MAINTENANCE/DISPOSAL, few participants appeared to consider the need for physical structures such as pedestrian bridges (the most commonly proposed solution in both years) to be inspected and repaired for safety. Given the same design task two years later, the students' responses did not change significantly with respect to life cycle considerations. A modestly larger number of students considered DESIGN/CONSTRUCTION, but none of the changes between Years 2 and 4 were statistically significant. Full coding results are shown in Table 2.

Although Large Public University was overrepresented in the sample, findings for participants at this institution were not statistically significantly different from those for the remainder of the sample, suggesting that the overrepresentation did not substantially skew the aggregate findings. The 15 LPU students who also participated in the interview did not differ substantially from the rest of the sample with respect to consideration of life cycle.

Overall, engineering students appear to evaluate solutions to the street crossing design task by imagining the complete solution in place. Most students in our sample did not consider other important stages in their solutions' life cycles,

Table 1. The four codes for consideration of life cycle in responses to Question (2) and (3) of the street crossing design task

Life cycle stage code	Description
CURRENT STATE	consideration of the problem scenario or circumstances before design or construction of a solution begins
DESIGN/CONSTRUCTION	consideration of the process (*vs.* outcome) of design/construction of a solution; includes ease/simplicity of construction but excludes general references to overall project cost (See SOLUTION IN PLACE.)
SOLUTION IN PLACE	consideration of a solution as installed and operating normally, after construction is complete; outcome (*vs.* process) of design/construction
MAINTENANCE/DISPOSAL	consideration of maintenance, modification, removal, or disposal of a solution; includes consideration of solution life span

Table 2. Number and percentage of longitudinal sample (N = 58) whose Question (2) and (3) responses discussed each of the four life cycle stages, as coded in our study. None of the changes from Year 2 to 4 were statistically significant

	Year 2	Year 4
CURRENT STATE	32 (55%)	22 (38%)
DESIGN/CONSTRUCTION	15 (26%)	25 (43%)
SOLUTION IN PLACE	58 (100%)*	58 (100%)*
MAINTENANCE/DISPOSAL	10 (17%)	12 (17%)

* Both questions asked specifically about solutions, so all students were expected to consider this stage; these statistics are included for completeness.

with less than half considering the design/construction process and fewer still looking ahead to long-term maintenance or disposal. Notably, our longitudinal analysis suggests that two years of studying engineering did not prepare students to consider life cycle more broadly. This limited consideration of life cycle is particularly notable, given the nature of the street crossing design task and that students commonly selected solution approaches involving substantial physical infrastructure (*e.g.*, pedestrian bridge). Life cycle is well-suited for comprehensive evaluation for criteria that are particularly important to projects of this nature, such as cost and safety, not to mention environmental impact.

To better understand the relationships among engineering students' conceptions of sustainable development, their educational experiences, and their consideration of life cycle during the design process, we next take a closer, more holistic look at the experiences, stories, and behaviors of four distinctive students in our sample of 15 at Large Public University.

3.5 The link between learning experiences and conceptions of sustainable development in engineering: A tale of four students

In the previous discussion, we considered dominant ways that students talked about sustainable development and how they performed on an engineering design task with respect to sustainable development as instantiated in life cycle analysis. In this section, we shift our lens to the students themselves in order to raise such questions as (1) Where do students' conceptions of sustainable development come from? (2) What educational experiences would help students to gain a more sophisticated understanding of sustainable development? and (3) What educational experiences and conceptions of sustainable development are accompanied by broad consideration of the life cycle while engaged in engineering design? We present four case studies of students discussing their learning experiences within and beyond engineering classrooms. These case studies illustrate the variety of learning experiences that students may have had that introduced them to notions of sustainability and the life cycle. Students themselves identified a variety of learning experiences to be significant and/or relevant to their understanding of sustainable development: internships, co-ops, work in research laboratories, and extracurricular and co-curricular activities.

The four students described here represent the range of responses to the sustainable development questions and the street crossing design task. We juxtapose short descriptions of students' learning experiences and conceptions of sustainable development with their responses to the engineering design task, with the intention of drawing attention to how the variety of their individual experiences associated with an engineering education program could in some way influence their ability to respond to the engineering design task.

Jesse

Jesse is a socially conscious engineering student who has participated in alternative spring breaks through Hillel (a Jewish student organization) and Engineers Without Borders. It should come as no surprise that his comprehension of engineering as a field of study and a profession are both shaped by his social consciousness. As a mechanical engineer who defines engineering as a 'noble pursuit to provide . . . community and the world with safety and improve the standard of living' of the world's people, Jesse contends that engineers must be prepared to handle large challenges. It is worth noting that when we asked Jesse to describe the most significant learning experience that he had as an undergrad, he mentioned his Hillel experience in Nicaragua, which became a significant service experience for him. Aside from his experience with Engineers Without Borders and in Nicaragua, Jesse had two internships as a mechanical engineer working on designs. Jesse believes that he is prepared to tackle the NAE's sustainable development aspirations for the engineer of 2020, yet Jesse adds that his exposure to the qualities entailed in those aspirations did not occur inside the engineering curriculum. Rather, his comprehension of social sciences, humanities, economics and sustainable development has been nurtured through his work in Engineers Without Borders and his overall social consciousness. In discussing the required skills of an engineer, Jesse mentioned that he had several difficult experiences working in teams. Jesse's comprehension of sustainable development, which we introduced in the previous section, highlighted a dimension that neither NAE nor the United Nations' [12] definition of sustainable development explicitly recognized: that limited resources include intellectual resources. That is to say, Jesse appears to interpret 'sustainable resources' more broadly than in the NAE's aspirations. Jesse's consideration of life cycle in engineering asserts that the maintenance of sustainable projects includes developing the intellectual resources necessary for a community to become self-sufficient with respect to the engineering solution at hand.

Emphasizing self-sufficiency as a goal in assisting developing communities suggests an ability to take the 'long view,' considering the long-term efficacy of a solution. In contrast, Jesse's responses for the street crossing design task lack such forward-looking considerations. In terms of the life cycle coding, his evaluation of potential solutions did discuss the design and construction stage of the life cycle but not maintenance and disposal.

Elizabeth

During four years at Large Public University enrolled as a computer science and engineering major, Elizabeth has had three internships with both large and small companies and two research projects on campus working with faculty. At each of her internships, she was given a mentor and has kept in touch with some of them. She has also sought advice from graduate students with whom she has worked on the research projects. As a student who has had the opportunity to have multiple internships and research projects, it is interesting to consider Elizabeth's opinions on these two disparate aspects of engineering. Elizabeth enjoyed working in industry more than research primarily because in industry she enjoyed having a final product that would be implemented. 'In research,' Elizabeth contends, 'you don't really know what's gonna happen. You're just trying to look for an answer and a solution, and then you don't know what the end result is gonna be.'

Despite having had experience in both industry and research, Elizabeth did not exhibit a strong comprehension of sustainability and the life cycle in design. Furthermore, consistent with Elizabeth's apparent lack of a clear understanding of sustainable development, her responses to the street crossing design task did not consider life cycle very broadly. Her evaluation of solutions considered traffic flow and pedestrian safety but neither the construction process nor maintenance issues. Perhaps her choice of words in describing her industry experience, where there is an 'end result,' indicates a temporally narrow scope that hampers consideration of what happens to a product or system once deployed or released to a customer or market.

Kara

As a mechanical engineering major, Kara believed that some important skills for engineers to have were the ability to network and communicate with other people, and the ability to gather a variety of information on one's own while working on engineering designs. This latter skill can be referred to as self-directed learning. Kara mentioned that she acquired self-directed learning skills both while working in her two internships at large engineering firms, and while enrolled in a course at Large Public University called 'Sustainable Development,' in which she worked on a project that involved a real-world engineering problem. Kara mentioned her senior design capstone course as the most significant learning experience she had had at Large Public University. For her capstone, Kara worked in a group of three to research, design, and implement a project for an actual client, and she related that the experience was especially important because 'there was no other way to go about it, other than to kind of throw you off the end of the dock and say, okay, we've given you all the tools, now go use them.' Given her experience in the sustainable design course, capstone work, and internships, it is not very surprising that Kara had very sophisticated responses to the questions we asked about sustainable development, where she was able to introduce some notions from the life cycle of design into her response.

Accordingly, Kara's street crossing design task responses stood out within the sample by demonstrating broad consideration of the life cycle. Her responses detailed the design process, suggesting both a preparatory study of traffic patterns and a trial implementation of new light timings before finalizing a solution. She also discussed the possibility of her proposed solution being adapted or even replaced, if it proved ineffective in the long run. Kara's formative experiences with respect to sustainability helped her develop self-directed learning skills and probably account for her sophisticated conceptions of sustainability and broad consideration of the life cycle during engineering design.

Matthew

Matthew is an aeronautical and aerospace engineering major who had no internship experiences but did have research experience in an aerospace lab. In the lab, Matthew learned to design and machine parts and obtained hands-on experience about processes and theories that he was learning in class. As such, Matthew defined working in this aerospace lab as his most significant learning experience, because he was able to apply theoretical concepts that he was learning in a class he was taking concurrently while working in the lab. 'We learn about this stuff in lecture and it's all kind of theoretical and out there, and then go to the lab and I can actually like look at the data and see this is real. . . . So it was cool in that regard.' While he was working in the lab, Matthew also developed relationships with two faculty members who became his mentors, guiding and advising him on his coursework and his future aspirations to attend graduate school and continue his studies in the aerospace field. Despite Matthew's hands-on experience working in the laboratory, he did not include aspects of the life cycle in his responses on sustainable development. As noted previously, Matthew referred to sustainable development as relating to the environment in some manner. At the same time, Matthew introduced the idea that engineering should be socially responsible.

As in Elizabeth's case, Matthew's vague and limited discussion of sustainable development was accompanied by a set of street crossing design task responses with limited consideration of life cycle. He considered neither the design and construction processes nor maintenance and disposal, shaping his decision-making process in terms of trade-offs between the current state of the intersection and his proposed solution in place. Given their industry internship experience, both Matthew and Elizabeth's cases might point to a missed opportunity to impress upon engineering undergraduates the importance of the temporally broad view that life cycle analysis and considerations of sustainability can facilitate.

4. DISCUSSION AND IMPLICATIONS

In this mixed-methods longitudinal study, we asked students to talk about sustainable development, and also analyzed their performance on an engineering design task to see if they incorporated issues of sustainability across the life cycle in their approach to engineering design. We found that while students often talked about sustainable development in terms of limited resources and the life cycle of engineered products, relatively few considered the life cycle when actually engaged in engineering design.

In taking the limited resources stance, a student may have considered sustainable development to be an important aspect of engineering; Ethan saw it as a motivation to become an engineer and Jesse saw limited resources as a set of problems for which engineers are responsible to solve. At the same time, acknowledgement of limited resources alone may not be adequate for full consideration of sustainability in engineering design. As evidenced in most life cycle narratives, limited resources are but one facet of a life cycle framework.

The life cycle stance seemed to offer students greater opportunity to discuss engineering design concepts more explicitly. Other students who discussed the life cycle connected it with engineering design. Amanda referred to design constraints introduced by the local, natural environment and Justin described sustainable development and life cycle within the specific context of his engineering sub-discipline. Michael considered the life cycle as integral to the engineering problem-solving process, and Kara described how gathering information about user priorities would be an important element of life cycle analysis.

An in-depth look at four of the students in this study illustrates how learning about sustainability is or is not transferred to performance on new engineering design problems. Jesse and Kara both had a broad range of learning experiences that introduced them to concepts of sustainability, yet Kara articulated a more sophisticated understanding of sustainability, and only Kara performed as well on the street crossing task as one might expect, given her experiences. One distinction that we can make between how these two students understood their learning experiences is in Kara's focus on the value of being capable of self-directed learning; that is, being able to identify what one needs to know, make a plan for how to learn it, and seek out and find relevant learning resources [13]. The development of skills necessary to direct one's own learning may account for the difference in Kara and Jesse's abilities to process their experiences into conceptions of sustainability that may be transferred and applied to novel situations.

Another distinction lies in the preconceptions students bring to the question of sustainability. Jesse's focus on ensuring that communities become self-sufficient in terms of knowing how to operate and maintain engineered products may have closed off his ability and inclination to learn new concepts that speak to limited resources and other aspects of the life cycle (see, *e.g.*, [14]). Furthermore, Jesse perceived that his preparation to incorporate sustainable development in engineering practice did not come from his formal engineering education, but rather from external opportunities for service learning. This disconnect between knowing and doing may be a product of Jesse's understanding of his engineering education where sustainability was not addressed, in contrast to the real (in his case, third) world where sustainability is the focus. The street crossing problem may have appeared to him more like the homework problems he solved for his classes than the development problems he solved in communities abroad. This case supports an argument for making sustainability and sustainable development concepts explicit in engineering classrooms and curricula, enabling students to transfer these concepts back and forth between simulated and real-world learning contexts.

Like Kara, Elizabeth had a broad range of applied learning experiences but was unable to offer any definition of sustainable development at all, nor did she consider the broad life cycle in the street crossing problem. Her preference for an 'end result' may imply a preconception about engineering design that is limited to the solution in place, rather than the entire life cycle of an engineered product. Matthew's vague conception of sustainable development, accompanied by limited consideration of the life cycle during engineering design, may also have been a product of his preconceptions about engineering design and sustainability. Matthew limited his discussion of sustainable development to natural environmental issues. He might have been unaware of the importance of these issues in aerospace design, leading him to regard sustainability and the life cycle to be irrelevant to engineering design in the context of his major.

Facilitating the development of self-directed learning skills and the ability to critically reflect on one's experiences may improve students' abilities to form conceptions of sustainability and incorporate them into their engineering design practices. Engineering educators and program planners should work not only to make sustainability explicit in engineering curricula, but also to provide opportunities for students to develop self-directed learning and critical reflection skills, to encourage the transfer and use of knowledge about sustainable development in a variety of contexts.

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Deborah Kilgore is a research scientist at the University of Washington's Center for Engineering Learning and Teaching and is also a research team member for the Center for the Advancement of Engineering Education's Academic Pathways Study.

Andrew Jocuns is a research scientist and team member for the Center for the Advancement of Engineering Education's Academic Pathways Study.

Ken Yasuhara is a research scientist at the University of Washington's Center for Engineering Learning and Teaching and is also a research team member for the Center for the Advancement of Engineering Education's Academic Pathways Study.

Cynthia J. Atman is the founding director of the University of Washington's Center for Engineering Learning and Teaching. She is also the principal investigator and director of the Center for the Advancement of Engineering Education.