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Assessing sustainability knowledge: a framework of concepts

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Assessing sustainability knowledge: producing a framework of critical concepts

Abstract
Although engineering professional societies and other governing bodies emphasize the necessity of sustainability in engineering education, these principles have proven difficult to integrate into existing engineering curricula. This paper describes activities designed to generate a framework of concepts engineering faculty members not familiar with sustainability can use to incorporate sustainability into their mid-level undergraduate courses. The research team conducted a variety of qualitative studies, including reviewing course descriptions related to sustainability, coding literature that talked about sustainability in engineering education, talking with undergraduate students about what they thought sustainability is, and learning from sustainability education experts through an online conversation and face-to-face workshop. The paper focuses on the final of these approaches, and describes the experiences and conclusions of working with sustainability education experts to formulate the framework of critical sustainability concepts. We propose the framework itself for discussion, and offer some final insights to consider for future work.

Introduction
Environmental sustainability is an increasingly critical concept for engineering students to incorporate into their macroethical and practical conceptualization of engineering work.
As early as 1999, the American Society for Engineering Education (ASEE) Board of Directors recognized this need and declared, in an official statement, “ASEE believes that engineering graduates must be prepared by their education to use sustainable engineering techniques in the practice of their profession.”[1] Engineering professional disciplinary societies have responded by including sustainability as part of Engineers’ Codes of Ethics: the first “fundamental canon” of the American Society of Civil Engineers (ASCE) Code of Ethics includes that engineers “shall strive to comply with the principles of sustainable development;”[2] the American Institute of Chemical Engineers (AIChE) includes “protect the environment” among the “paramount duties” of engineers;[3] the American Society of Mechanical Engineers (ASME) Code of Ethics instructs engineers to “consider environmental impact and sustainable development”[4]; and the National Society of Professional Engineers (NSPE) lists as a “professional obligation” the responsibility to “adhere to the principles of sustainable development in order to protect the environment for future generations.”[5] These statements have international counterparts: the World Federation of Engineering Organizations (WFEO) “encourages all engineers to become knowledgeable of sustainable development principles and … the current sustainable development technologies applicable to their work.”[6]

Furthermore, the Accreditation Board of Engineering and Technology (ABET) general outcome criteria for 2014-2015 include sustainability issues in at least two of the sub-points: criterion 3(c) explicitly cites “sustainability” as a design constraint that students should be able to address, and criterion 3(h) stresses the importance of a broad education that allows engineering solutions in societal context, an important aspect of sustainable engineering (ABET Board of Directors, 2013).

However, most engineering students (excluding those focusing on environmental issues) have little opportunity to engage with the topic in their general or major-specific engineering curriculum, and few engineering faculty members (again outside of environmental or ecological engineering) have the content knowledge necessary to prepare students for working in engineering contexts dealing with the realities of climate change and diminishing global resources.

To that end, we conducted a progressive series of educational research studies to develop a framework to help a broad range of engineering faculty members determine how to incorporate sustainability into their mid-level (sophomore and junior) traditional technical engineering courses. Our idea was to propose a framework of concepts for assessment that untrained engineering faculty members could incorporate into assignments and exams that would therefore function to help them put appropriate sustainability content into those mid-level courses.

Our larger project includes five major areas of work, some of which have been published previously. This paper will focus on the fifth area, where we discuss with sustainability education experts what they think should be in our assessment framework through a professional conference, online conversations, and a workshop, and we introduce the framework itself.

First, however, in the interest of providing context, here are summaries of all five studies:

(1) To develop this framework, we began by doing a *content analysis of existing literature* published on sustainability in engineering education.[7] We found ecofeminist theory[8–10] and polarity management tools[11] useful for understanding why sustainability remains a marginalized topic in engineering and engineering education. Ecofeminist theory prompts us to question dualities, particularly those where ideas and values we culturally associate with "masculinity" subordinate those we associate with "femininity." A common duality that ecofeminists problematize is the culture-nature duality, or the technology-nature duality, which fits well into the varying discourses around environmental sustainability. Polarity management, although it comes from a very different literature, has a similar purpose: to problematize the conceptualization of a "good/bad" dichotomy, and instead to consider poles each with strengths and weaknesses. We used these two ideas to catalogue the ways that sustainability was discussed in the existing engineering education literature.

We developed three comprehensive themes with several subthemes that describe much of the literature on sustainability and engineering education:

1. Sustainability as a skill set for the future engineer. Subthemes: Super engineer vs. traditional engineer; conventional vs. contemporary engineering practices; Employability; Engineers as problem definers, problem solvers and more; and Role of technology in sustainable engineering.
2. Sustainability (in)disciplined. Subthemes: Sustainability as a discipline by itself, or a component of existing disciplines; Sustainability as an interdisciplinary concept; and Sustainability as "normalized" versus "soft."
3. Sustainability as value-based engineering. Subthemes: Sustainability in relation to industry; and Sustainability as a value.

Through these themes, as prompted by both the theoretical frames of ecofeminism and polarity management, we noted that the way sustainability is rhetorically discussed in engineering education is key to both its marginalization and its subsequent incorporation. So, for example, if sustainability is considered "value-laden" and therefore should not be incorporated into engineering education, making visible the other implicit values incorporated into engineering[12–14] could open a metaphorical door to admitting sustainability as an engineering topic.

(2) We *collected and thematically analyzed statements of sustainability* published by a variety of governmental, industrial and commercial, and academic institutions to see what people were arguing were critical components of sustainability.[15] A systematic survey of these statements of principles (or definitions) of sustainability in the engineering context shows a wide variation in the content and emphasis. In our analysis, the principles included in fifteen major published sets of principles could be summarized in six categories:

1. traditional environmental engineering goals
2. specific items to protect or improve,
3. social and societal aspects,
4. ethics and guiding beliefs,
5. engineering design tools, and
6. business and economic perspectives.

While this organization of principles may not be surprising, we found some interesting patterns: few individual sets of principles addressed all six areas, and a disproportionate emphasis was placed on the first two areas.

(3) We also did a complementary *content analysis of a survey of course descriptions and titles* to see what faculty members at universities across the country articulated as related to "sustainability."[15,16] The descriptions of these sustainability-related courses in engineering at major US universities showed a strong bias toward the first two thematic areas (environmental engineering and resource protection). The published descriptions of courses show a narrow definition of sustainability, centered on pollution prevention, waste reduction, efficiency, resource conservation, renewable energy, and life cycle analysis. Mentions of social, ethical, or economic dimensions of sustainability, when they exist, are general and non-specific.

(4) We *interviewed undergraduate engineering students* to see what they were learning that constituted sustainability.[17] Though a grounded-theory informed analysis, we determined we could treat sustainability as a *threshold concept*[18] as students self-reported coming to understand sustainability as a *transformative* event which was also *irreversible* (or, at least, not easily forgotten or "unlearned"), that it was *integrative* in that it exposed previously hidden interrelatedness, and that it was *troublesome* in its lasting impact on students. This conception of sustainability as a threshold concept was despite the fact that the three most prominent interpretations of sustainability were fairly naïve: sustainability was about increasing efficiency, reducing consumption, and using less material to get the job done.

(5) Finally, we attended and observed *public professional discussions* of technical engineering academics focused on sustainability and education and we convened *a workshop of sustainability education (in engineering) experts* to conduct intensive discussions about what a framework of sustainability education for engineering students should include.

This paper describes this last activity and summarizes the project: we outline the set of ideas we gleaned from the preliminary activities, the design of the workshop and the collection of participants, key ideas raised in the workshop discussions and the framework that we have subsequently developed based on all these pieces together. This framework is based on concepts we have dubbed "gateway concepts" in that they are opportunities to easily hook sustainability concepts to traditional engineering educational content but have the potential to allow students to dive much deeper into content should faculty members provide those opportunities. We provide illustration of these gateway concepts, and demonstrate the overall framework's use for guiding faculty members' curriculum development.

Pre-Workshop activities and ideas

Selecting workshop participants

The planning and implementation of the Assessing Sustainability Knowledge workshop was a multi-dimensional component of the overall project. The workshop's goal was to synthesize key sustainability concepts and relationships into a framework that can be used to guide assessments of sustainability knowledge.

In the fall of 2010, we put together a list of potential candidates that we wanted to invite, based on their content expertise, their authorship of compelling or provocative articles on sustainability in education, their reputation for divergent or innovative thinking, and the kind of institutions they had been a part of. Once we had a master list of potential candidates, our graduate assistant created profiles on their work, addressing the multiple aspects we were interested in incorporating into the group including: type of institution, connection with industry, environmental studies, or engineering, and teaching undergraduates. We discussed the combination of candidates and created a list of 8 people we would like to involve and a new timeline against which to work. We invited each one individually in November and December, and all 8 people agreed to participate starting in January 2011.

Our expert group consisted of (alphabetically):

- Braden Allenby, Arizona State University
- Andy Lau, Penn State University
- Jean MacGregor, Washington Center for Improving the Quality of Undergraduate Education, The Evergreen State College
- Jim Mihelcic, University of South Florida
- Cynthia Murphy, University of Texas-Austin
- John Petersen, Oberlin College
- Thomas P Seager, Arizona State University
- Linda Vanasupa, California Polytechnic State University, San Luis Obispo

Online conversations pre-workshop

Prior to our face-to-face workshop in May 2011, we enrolled all eight experts, the core research team, and the project's consultant onto a Google Group to help archive the discussion and any documents distributed through the list. We initiated some online conversations to jumpstart our face-to-face conversation scheduled for the workshop. Our prompts to start discussion by email were:

- "February: By email, introduce yourself, and share with us your philosophy of sustainability, including through sharing your top 3 articles (yours or others) that represent your views.
- March: By email, share where do you think sustainability education/engineering education is stuck? Where does the current state of education miss the point, or focus on counterproductive ideas?
- April: By email, share what ideas or concepts should be assessed in this area? (What, not necessarily how...)"

The core research team read these online conversations (as well as any associated references the participants sent out) and summarized them at our regular meetings.

February discussion (top three articles):
While the introductions were interesting and illustrative of the group we had selected, for the purposes of this paper we list the resources that participants recommended in Table 1.

Table 1: List of alphabetized references illustrating workshop participants' perspectives on sustainability

1. Allenby, Brad (2010) "Climate change negotiations and geoengineering: Is this really the best we can do?" *Environmental Quality Management* 20(2) 1-16
2. Allenby, Brad (2011) "Emerging technologies, military operations and national security: Fundamental drivers for development and deployment of radical technologies" *International Symposium of Sustainable Systems and Technology (ISSST)* May 16-18 2011 Chicago
3. Allenby, Brad, and Jonathan Fink (2005) "Toward Inherently Secure and Resilient Societies" *Science* 309(12 August) 1034-1036
4. Bell, Simon and Stephen Morse (2005) "Holism and Understanding Sustainability" in *Systemic Practice and Action Research* 18(4) August,409-426 DOI 10.1007/s11213-005-7171-9
5. Burgis, Laura and Laura I. Rendón (2006) "Learning with heart and mind: embracing wholeness in learning communities." *Religion & Education 33(2)* Spring 2006 pp. 1-19
6. Freese, Barbara, 2004. Coal: A Human History. Penguin Books.
7. Jacobs, Jane. The Economy of Cities (1969) or The Nature of Economies (2001), both from Vintage Press
8. Lau, Andrew (2010) "Sustainable Design: A New Paradigm for Engineering Education" in International Journal for Engineering Education, 26(2) 252-259
9. Lau, Andrew S. (2004) "Life-centered Design - A Paradigm for Engineering in the 21st Century" ASEE 2004
10. Lau, Andrew S. (2010) A Philosophy of Sustainability for the 21st century. In Materials Research Insittute, PSU, Summer 2009.
11. Lubchenco, Jane (1998) "Entering the Century of the Environment: A New Social Contract for Science" *Science* 279(23 January) 491-497
12. McConville, J.R., and J.R. Mihelcic, "Adapting Life Cycle Thinking Tools to Evaluate Project Sustainability in International Water and Sanitation Development Work," Environmental Engineering Science, 24(7): 937-948, 2007.
13. Meadows, Donella (1997) "Places to Intervene in a System" *Whole Earth* Winter 1997, http://www.wholeearth.com/issue/2091/article/27/places.to.intervene.in.a.system
14. Mihelcic, J.R., "The Right Thing to Do: Graduate Education and Research in a Global and Human Context," in What Is Global Engineering Education For? The Making of International and Global Engineering Educators (Eds: G.L. Downey and K. Beddoes), Morgan & Claypool Publishers, San Francisco, pg 235-250, 2010.
15. Mihelcic, J.R., J.C. Crittenden, M.J. Small, D.R. Shonnard, D.R. Hokanson, Q. Zhang, H. Chen, S.A.

Sorby, V.U. James, J.W. Sutherland, J.L. Schnoor, “Sustainability Science and Engineering: Emergence of a New Metadiscipline,” Environmental Science & Technology, 37(23):5314-5324, 2003.

16. Orr, David (1997) "Architecture as Pedagogy II" *Conservation Biology* 11(3) 597-600
17. Parks, Sharon Daloz (2005) *Leadership Can Be Taught,* Ch 1. Harvard Business School Press.
18. Petersen, John E (2008) "A Green Curriculum Involves Everyone on the Campus" *Chronicle of Higher Education* June 20, 2008 54(41) A25
19. Ponting, Clive, 1993. A Green History of the World: The Environment and the Collapse of Great Civilizations
20. Seager, Thomas, Evan Selinger, Arnim Wiek (2012) "Sustainable Engineering Science for Resolving Wicked Problems"*Journal of Agricultural Environmental Ethics* 25(4) 467-484
21. Seager, T. P., Fraser, M., & Wiek, A. (2011). A sustainability science approach to the superfund research program.
22. Sherman, Daniel J. (2008) "Sustainability: What's the Big Idea? A strategy for transforming the higher education curriculum" *Sustainability* 1(3) 188-195 DOI 10.1089/SUS.2008.9960
23. Speth, J.G., 2008. The Bridge at the Edge of the World: Capitalism, the Environment, and Crossing from Crisis to Sustainability,
24. Vaclav Smil, Carbon Nitrogen Sulfur: Human Interference in Grand Biospheric Cycles (1985) Springer.
25. Vanasupa, Linda, Roger Burton, Jonathan Stolk, Julie B. Zimmerman, Larry J. Leifer, Paul T. Anastas (2010) "The systemic correlation between mental models and sustainable design: implications for engineering educators" *International Journal for Engineering EDucation* 26(2) 438-450
26. Winner, Langdon (1986) "Do Artifacts have politics?" Ch 2 in *The Whale and the Reactor,* Chicago University Press
27. Wright, Ronald, 2005. A Short History of Progress. Da Capo Press.

March discussion: where are we stuck?

The main area of this lively conversation evolved over two weeks, with an initial focus closer to the posed question, and a later focus on more philosophical issues about the place of science and engineering (together and separate) in knowledge creation and in an ethical context of society. Notable throughout is the concentration on big picture ideas. There was very little discussion about material in engineering or sustainability education that causes problems or issues, but much more discussion on the framing of sustainability in the first place, the structural positioning of sustainability thought within the existing educational and academic paradigms (or, often, in contrast to the existing paradigms) of science and engineering, and the relationships of sustainability (an, in fact, science) to values, ethics, and epistemology.

The comments had an almost-universal anti-reductionist current. Several posts pointed out the need to move beyond traditional reductionist approaches and frames of mind, and “industrial-age science,” and move toward a different paradigm. The feeling of the dialogue as a whole is really revolutionary; that the main place where we are “stuck” (the broad *we* of all Engineering Education, not the narrow *we* of the people in this dialogue) in sustainability education arises from the reality of accomplishing only incremental changes (even worthwhile ones) instead of revolutionary epistemological changes.

The posts highlighted the need to be mindful about the implications of how sustainability education interacts with the things that science and engineering education has been hesitant to touch – ethics, values, politics, truth (or “capital-T Truth”), and belief. Several posts noted the need for sustainability education to explicitly embrace these concepts, in ways that starkly contrast current thinking of what science and engineering are (hence the need for revolution).

The conversation indicated that a student's understanding of some of the existential questions of science and engineering may be pre-requisite to their understanding of sustainability. We wondered if this meant that assessing scientific and engineering ways of knowing and science's and engineering's interactions with other realms of knowledge should be part of assessing sustainability knowledge.

The conversation took the form of over 25 email strings, some with dozens of replies, comments, and discussion points. To help summarize the overall conversation and create a very brief summary of the main idea of each contribution, we developed a list a single "capturing" phrases or words (in no particular order) from each string. These capturing phrases are:

integrative
wicked problems
rules of engagement
meaning
restructuring
seeing our thinking
overcompensating for fears
incremental
why science
holistic science
faith
mode of inquiry
models
unexamined bias
normative
flourishing
technology mode
rules of argument
modes of evidence
colossal challenges
set of values
value neutrality
experiments
imposing values
authority
design
science vs. engineering

April discussion: what should be assessed?

This conversation was shorter than the previous two, but still included some useful thoughts for creating the framework. One of the expert workshop participants (MacGregor) challenged the group to ask what one concept, one skill, or one habit of mind, would you want students to learn if you knew they could not fail. Another expert participant (Vanasupa) responded to this question by listing a set of 5 ideas with systems and relationships at their heart (the following is excerpted directly from an email):

1. "The capacity to manage our individual and collective attention --to see our seeing. ([…]... concept: attention ultimately defines the action)
2. The capacity to see one's own participation in dynamic human systems (concept: system behavior is a result of [how the] system functioning [is] designed [by humans, System functioning perfectly depends on proper design.]); [Bracketed text added by authors to improve readability in this context.]
3. A disposition of responsibility around one's own actions, including the action of thought (concept: thought=action is from D. Bohm, concept: thought creates systemic structures, systemic structures condition systemic behavior and therefore, thoughts ultimately produce systemic behavior)
4. A disposition of discovery, of welcoming difference and conflict as the visible opportunity to learn about another's mental models, and of seeing and experimenting in one's own life (concept: sustainable solutions are local and emergent and therefore require active experimentation and learning)
5. A disposition of positive regard toward "others," in a recognition of our deep and undeniable interconnectedness (concept: our fundamental condition is that of interdependence)."

A third expert participant (Lau) also weighed in to present three "pictures" of what he tries to assess in his students' work, using a hierarchy of big ("emphasizes connectedness, compassion, and participative reality and evolution"), medium ("systems thinking of […] the kind that ecologists and geoscientists think of which is about life/earth/cosmos systems"), and small ("Ability to understand and use analytical/assessment tools like LCA, Eco-footprint, risk, etc. in the design of new things").

These conversations informed the development of our initial gateway concept framework. However, rather than through a systematic qualitative analysis informed by grounded theory and conducted through Dedoose (a qualitative data analysis software package), the framework emerged as a collective construction from myriad conversations, where key topics were connected to the ideas to which we returned most.

Pre-workshop framing of ideas from various sources

The core research team and consultant scheduled a complete day in early May to plan the workshop schedule and to draft an initial framework for the workshop participants to discuss. Calling this our project's "Boot Camp," we aimed to have everyone finish the readings from workshop participants' January discussion response, as well as read through the rest of the email discussion. We also reviewed pseudonymized student interviews collected for a different part of the project to see if there was something here to bring in to the workshop discussion.

Our initial framework of gateway concepts (outlined below) emerged from a discussion at the Boot Camp that synthesized ideas from the expert workshop participants' online conversation, along with the summaries of the works they had used to represent their current thinking (outlined in Table 1), our previous published work [7,15,19,20] and our interviews with undergraduates talking about sustainability. We did not systematically analyze "data" from each mode to yield themes, but instead each Boot Camp participant brought up for discussion key ideas from each, and we "knitted" connections with our own ideas or other points in the discussion. It was a dynamic and nonlinear "analysis" rather than one done systematically in series.

We shifted across various metaphors during our discussion, trying to land on one that could hold the potential for representing the breadth and complexity of the collective data sources we had at our disposal. We considered using stage theory,[21] where students could be located at various "stages" of environmental sustainability knowledge, but that seemed too linear and reductive. We looked at using a reductionist lens as the defining characteristic of someone's openness to the types of sustainability topics we were discussing, and that seemed problematically binary.

Eventually, we wound our way into simply listing key ideas, at the highest level, that had the potential for the kind of depth of discussion our experts were having online. We framed them, then, as "gateway" concepts, a wink at the idea of "gateway drugs": as we described earlier, our interview data with students had already prompted us to think about sustainability as a "threshold" concept[18] in that it was transformative, irreversible, integrative, and troublesome from a variety of places. After this discussion, we felt that one could shallowly sample just one of these ideas, and it could lead one almost "naturally" to much deeper, integrated, systemic and holistic treatment of the other topics.

The gateway concepts had two important dimensions: (1) in addition to having a sustainability core, they are all indisputably *engineering* concepts; this would allow easy integration into an existing course and smooth transition from traditional engineering topics to the sustainability-related content (one meaning of "gateway"); and (2) they are all deeper concepts that can be applied across a wide variety of situations, and that can lead an engineering student to ask how a particular engineering problem has sustainability implications.

The initial gateway concepts were these:

- *Time:* The ultimate implications of an engineering solution over time are critical to sustainability; models of resource use typically don't adequately account for time and engineering timescales often deal with the length of the project rather than the life of the materials and resources.
- *Scale:* By necessity, engineers define boundaries around a project that determine what is included in the analysis and what is not; explicit consideration of scale, and if the scale of analysis is sufficiently large, can help engineers make decisions that are more sustainable in a global sense.
- *Feedback:* Complex dynamic systems may respond in unexpected ways if feedback forces are not considered; training engineering students to look for feedback effects from their designs, both in the engineered part of the system and the natural part of the system, will lead to better predictions of future effects and more sustainable outcomes.
- *Energy:* Energy is both at the core of engineering and the core of sustainability; students should be encouraged to include specific analysis of the broad energy needs (and potential sources) for all engineering projects.
- *Modeling*: Complex modeling of the impacts of an engineered system, including several of the dimensions above (energy modeling, feedback, modeling over large temporal and spatial scales) will enhance the ability to make sustainable decisions. Engineers need to be well versed in complex modeling tools.

Workshop implementation

Workshop design

Our primary goal for the workshop was to have enough conversation face-to-face to support the writing of a paper about these topics after the workshop was over. We knew we needed to provide enough space and time for the participants to just talk, that an over-scheduling of activities would backfire with this creative and innovative group of thinkers. As a result, we adopted a strategy of having diverging and then converging conversations, to take advantage of the heterogeneity of the expertise and the capacity of experts to connect to one another's ideas but also to focus on the main goal of the project: to develop a framework for assessing sustainability knowledge.

The workshop schedule ran for 1 ½ days: an afternoon and the following full day. We developed the schedule in Table 2, then proposed it for discussion and redesign at our first workshop session. The first afternoon was to spend time discussing what we had found already through the other phases of the work. The next morning was to be spent talking over "ideas worth sharing", and the final afternoon was to focus on the framework itself.

Table 2: Outline schedule of expert workshop, May 18-19 2011

Day 1	
afternoon	Session 1: Setting the stage Introductions (using 10 Faces of Innovation), workshop goals, house rules, agreeing on the plan for the workshop.
	Session 2: Making sense of what we have already (converging)
Day 2	
morning	Session 3: Ideas worth sharing (diverging)
	Session 4: Critical incidents (diverging)
afternoon	Session 5: Assessment framework (converging)
	Session 6: Where shall we go now? (wrap up)

Collecting insights from ISSST

The workshop was scheduled immediately following the 2011 International Symposium for Sustainability Systems and Technology (ISSST; ieee-issst.org) in Chicago, IL. This was done in part to facilitate travel for expert workshop participants (several of whom were already planning to attend the ISSST conference), and in part to observe ISSST to see if the presentations could help inform our work. One of our expert workshop participants (Seager) served on the program committee for ISSST, and invited us to attend the conference, present our work, and provide feedback to the symposium, in the form of a 90-minute discussion session. This session was based on observations we made at the other ISSST sessions, reflecting back to participants what we heard and saw but through the lens we were developing on sustainability. To prepare for the session, the research team spread across three concurrent sessions of ISSST, and took notes based on the following items:

1. What do people consider “sustainability”?
2. What are things our students should understand, know, be able to do?
3. Do we see evidence of our initial gateway concepts: Time; Scale; Feedback; Energy; Modeling
4. What mentions of contexts are made: values; social; political; technical
5. To what degree are conversations focused on US or globally?
6. Any mentions of corporate, industrial, governmental, educational contexts?
7. What did we miss in our pre-workshop data collection?

During one evening of the ISSST conference, the research team convened to talk over themes and observations from the sessions we attended. We developed a set of conclusions to share at our session the next morning, situated within the rest of our project data. Our observations’ conclusions were based on things we saw or heard in the sessions; however we acknowledge that we are motivated by our particular interest in the topic (as different people see and value different things).

In our observations, talks at ISSST tended to:

1. Focus on a technological solution.
2. Lack explicit definitions of sustainability.
3. Use implicit definitions of sustainability that had a heavy focus on energy, materials availability, toxicity, and waste reduction.
4. Set up economic concerns as dominating other concerns.

5. Only infrequently make policy recommendations.
6. Have common goals of minimization, maximization, and optimization.
7. Exhibit a tension between values-based decision-making and technology/quantitative-based decision making.
8. Have different approaches to treating complexity: there was sometimes a stated recognition of complexity of system, immediately followed by statement of need to simplify or concentrate on a sub-system.
9. Make motivations of the choice of sub-system explicit: area of large impact, area of high uncertainty, area with capacity and control to do something about it
10. Provide varying conceptions of relationship with nature.
11. Use varying conception of limits: limited resources v. limits to growth.
12. Use varying approaches to dealing with uncertainty.

Our feedback session at the end of the ISSST conference included few participants but was an active and vibrant conversation that provided some confirmation of the validity of our observations and our developing gateway concept list. The juxtaposition of our observations from the ISSST conference and our online conversations with our expert group was particularly striking. The language our expert workshop participants used (for example some of the "capturing phrases" from the March conversation, such as *integrative, meaning, seeing our thinking, overcompensating for fears, holistic science, faith, mode of inquiry, unexamined bias, normative, flourishing, modes of evidence, colossal challenges, imposing values, authority)* is extraordinarily different from the language we heard in these technical sessions.

This difference underscores a dilemma of sustainability in engineering: the ISSST technical sessions (and, to some extent, our initial gateway concepts) occur as a direct extension of the objective, mechanistic, and reductionist frame of mind that forms the foundation of science, and that most practitioners of science and engineering have been acculturated into. But true solutions to emergent complex social/technical systems require different ways of thinking. The reductionist, objectivist worldview focuses on materials and processes as a means to (sometimes benevolently) manipulate toward a desired outcome. This often works for simple systems of objects, but not complex systems of people, most certainly when there are ethical questions about manipulation in such as system.

However, it is probably fair to say that the ISSST observations are a reflection of where many practitioners of engineering are in the developing conception of sustainability. Because of the traditional reductionist and objectivist values of engineering as a profession, we should expect a list that is dominated by technological concerns, views technology optimistically, and is preoccupied with thermodynamic perspectives. But we can hope that engineering can shift; indeed, we believe the global situation demands it.

Running the workshop
After the ISSST session, we began our main IEECI-ASK workshop in the afternoon. The plan for the workshop that we had prepared at our Boot Camp day is outlined in Table 2. Each of the Purdue team members took copious notes, we audio recorded all discussions, and we have the written products of attendees (large flipchart paper, giant and small stickies, and so on).

Workshop outcomes, including final gateway concept framework

Despite our carefully-planned diverging/converging structure for the expert workshop, participants were more interested in spending time talking about topics in a free-flowing way than following a specific structure. Through detailed conversations, it became more clear that the group would not easily converge to consensus on a tangible set of topics critical for students' comprehensive understanding of sustainability. As a result, our endpoint of the workshop was a very different place than where we had anticipated. We understand now that our anticipated endpoint would have needed an increased level of consensus at the beginning than we had in the room. However, we are hypothesizing that this disagreement is not a bad thing, and indeed is something that characterizes the field of sustainability education –we see now that leaders do not usually see eye-to-eye in this area. We think our ecofeminist framework – which problematizes and then reweaves dualities, including those between technology and nature – can help us think about this discord.[7] In other words, we understand now that the disagreement on key content in and approaches towards sustainability engineering education is part of the community's fabric, and perhaps is endemic. So a framework that assesses sustainability knowledge may be more metacognitive than based in content.

One way we have tried to incorporate the metacognitive aspects is through the modification of our initial gateway concepts framework. Specifically:

- *Feedback* was modified to *Systems* to reflect the broader set of systems interactions that may be important, rather than feedback alone.[22] The broader conceptualization would include positive and negative relationships, stocks and flows, delays and oscillations, and reinforcing and stabilizing loops.
- *People* as a concept was added to reflect the importance of the consideration of social and socio-technical systems, as well as user-centered design, in the overall modeling and analysis of the sustainability of an engineering solution.

The metaphor of "gateway concepts" we still find a useful one for considering key assessment dimensions that can be applied to assess mid-level undergraduate engineering courses for their treatment of sustainability. Our current list of gateway concepts is therefore: *Time*, *Scale*, *Energy*, *Systems*, *Modeling*, and *People*. We illustrate these concepts in Table 3 in light of our conclusions, next.

Conclusion

We began this project thinking that sustainability content was not being introduced into engineering education primarily because most mainstream engineering faculty members did not know what to include. We now think that the most important ideas associated with sustainability are almost epistemologically counter to the type of engineering thinking that faculty members, often inadvertently, teach to undergraduates: one where you can put bounds around the system of interest, where you can treat that bounded system as though it was operating in isolation and you don't have to care where the waste stream goes, where you can reduce problems to simulacra where one knows and takes as given (and unproblematic) all the inputs and outputs. In contrast, our workshop experts' perspective was really system-oriented, focused on a rejection of reductionism and an embrace of a holistic way of looking at the world. Others have described the problems with this kind of reductionist thinking, [e.g. 9,22,23] and so we join our voice with theirs in calling for a reconceptualization of engineering education from the ground up.

In addition, we needed to rethink our goal of developing our framework as an assessment-oriented tool to scaffold content into the classroom. Traditional assessment models point to the identification of a relevant theoretical framework as an essential initial step in instrument development. However, in some cases, including ours, the main construct to be assessed by the instrument under development has been under-researched, such that there are not sound theoretical frameworks to serve as a foundation for instrument development. With this project, the process of engaging expert voices in an iterative manner through multiple forms of contact (email conversations, individual conversations and workshop conversations) yielded a theoretical framework that can serve as the basis for assessing sustainability. This is noteworthy as a model for how other researchers (across various education research communities) might begin instrument development projects where theoretical frameworks are missing or limited.[24]

Even within this limited canvas of students' engineering thinking, we believe our gateway concepts may prove useful to those faculty members looking for ways to bring more sustainability into their courses. However, we now consider "assessment" in a different light. Rather than look at assessment as a way for faculty members to judge students' learning in particular areas related to sustainability, our assessment framework can be considered a tool for both faculty members and students to use to consider existing reductive engineering problems in a more holistic light – so, *it is a framework both groups may use to assess the limits of one's solution, and from which to design more holistic solutions*.

We offer a 2-D illustration of this framework, expanded to the scope and depth we anticipate of undergraduate engineering contexts and learning, in Table 3. The table provides questions that a student or faculty member may ask to help guide evaluation of the sustainability of a proposed design solution. We see this framework of our gateway concepts as a way to help engineering students or faculty members to see sustainability concepts as engineering concepts, something we see people outside of engineering having been arguing for decades. We can envision expanding this model into 3-D, where one would take into account 3 gateway concepts simultaneously, as a useful exercise for more advanced students.

All the previous parts of our project have informed the construction of this framework. With respect to our ecofeminism critique, it should be able to help engineers see how values are a part of their normal work, and how consideration of sustainability should be thought of as a technical skill. With respect to our work with course descriptions and sustainability principles, it allows treatment of some of the lesser used of our 6 categories of ideas, including ethics and guiding beliefs, and social/societal aspects, and expands the definition of sustainability that multiple levels of different disciplinary courses might incorporate. With respect to undergraduates' definitions of sustainability, it should help students move past the limited definitions they reported, as well as demonstrate how sustainability should be considered part of "normal" engineering operations.[19] With respect to the expert conversations we observed, we believe it addresses some of the limitations we articulated regarding the ISSST sessions, and incorporates some of the depth of thinking, or at least encourages the exploration of this depth of thinking, offered by our workshop experts. And finally, it should help non-environmental engineering faculty members think about ways to accessibly incorporate sustainability thinking into their mid-level engineering courses.

Our next step for this framework is one of "groundtruthing." Based on the disciplinary expertise represented in our research team, we can see connections to many mid-level disciplinary courses. What do other faculty without our background see as possibilities or limitations? What will be the best ways to offer this framework for use to others? Could it be extended to first-year or pre-college engineering education settings? We could envision disciplinarily-specific illustrations of the framework (so, a Table 3 written for mechanical thermodynamics courses, or for industrial engineering safety courses, or for civil engineering structures courses, or electrical engineering junior design courses), and partnering with faculty in these disciplines in their construction might provide a better chance for the framework's adoption.

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Table 3: Sustainability assessment framework scaled for undergraduate engineering learning: questions for students or instructors to ask to help situate the sustainability issues and opportunities of a student design project.

	Systems	**Time**	**Energy**	**Modeling**	**People**	**Scale**
Systems	How does my system interact with other systems, or is situated within other systems? How have I considered positive and negative feedback cycles in my solution? How can I improve this treatment?	Over what timeframe am I considering my system operating in isolation? What data do I have to justify this decision?	Where does the energy my system is using come from? Where do the waste products go? What about when I expand my system one level? Two levels?	How do I decide the "edges" of my systems? How do I understand the tolerances of that decision? How can I model my "edges" to be as permeable (and therefore realistic) as possible? How do I incorporate in my model systems which we don't understand sufficiently yet?	What people are my system boundaries allowing me to think about? Why are other people excluded? How do I think about my responsibility to "do right" by anyone touched by my solution, whether inside my system boundaries or not?	How will the boundaries of my system change when I consider the use of my system at scale?
Time		Over what timeframe is my solution operating? What data do I have to support these time-based decisions?	Over what timeframe can I count on this energy source?	Over what timeframe is my model valid? What are the risks of extending the model's use beyond that timeframe?	How will the people that my solution influences likely to change over time?	How does the timeframe of my solution influence scale? How does the scale change with time?
Energy			What energy have I designed my system to use? How much energy will it take to produce my system? What about in the waste-stream?	How do I model my solution's energy use for production, use, repair, waste, and decay?	How does my chosen energy source influence: • who can use my solution? • where my solution can be useful? • who bears the costs of my solution's operation, repair, waste, or decay? How do I minimize energy usage, or design my solution to be flexible in its energy source?	How will scale of production, use, waste and decay prompt me to make different energy-oriented decisions for my solution?
Modeling				How are the decisions I'm making about my solution functioning as	Who bears the risks of my modeling decisions, including timeframe and	How does considering my model's use at large

				a model I am constructing about the problem, as well as how the world "works"?	scale of operation, system boundaries, and energy use? What do I do to erase those risks?	scale change my design decisions?
People					How are the populations who experience benefit from the solutions different from those who experience the problems? How do I justify my responsibility in a larger holistic framework of engineering practice, and then in a framework of global citizenship? How do I design not simply defensively (to minimize risk) but instead design to *increase* wellbeing of the planet?	When I consider my solution's implementation at scale, what new groups of people do I influence? How do I work to increase justice through this solution rather than diminish it?
Scale						How much energy does my solution use in production, in use, in decay, at the scale of production I am considering?