The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
Paper ID #41492

Addressing Issues of Justice in Design Through System-Map Representations

Dr. Alan Cheville, Bucknell University

Alan Cheville studied optoelectronics and ultrafast optics at Rice University before joining Oklahoma State University working on terahertz frequencies and engineering education. While at Oklahoma State he developed courses in photonics and engineering design. After serving for two and a half years as a program director in engineering education at the National Science Foundation, he served as chair of the ECE Department at Bucknell University. He is currently interested in engineering design education, engineering education policy, and the philosophy of engineering education.

Dr. Stewart Thomas, Bucknell University

Stewart J. Thomas received the B.S. and M.Eng. in Electrical Engineering from the University of Louisville in Louisville, Kentucky in 2006 and 2008, respectively, and the Ph.D. in Electrical and Computer Engineering from Duke University in Durham, North Carolina in 2013. He has served on the organizing committee for the IEEE International Conference on RFID series since 2014, serving as the Executive Chair in 2022, with research interests in areas of low-power backscatter communications systems and IoT devices. He is also interested in capabilities-based frameworks for supporting engineering education. He is currently an Assistant Professor at Bucknell University in the Electrical and Computer Engineering Department, Lewisburg, PA USA.

Dr. Rebecca Thomas, Bucknell University

Rebecca Thomas is the inaugural director for the Pathways Program at Bucknell University, where she oversees the rollout of Bucknell's ePortfolio initiative. She is also a Teaching Assistant Professor in the Department of Electrical and Computer Engineering where she instructs the first-year design course for ECE majors. She holds a B.S. and M.Eng. in Electrical Engineering from the University of Louisville and a Ph.D. in Electrical Engineering from North Carolina State University.

Using System Map Representations in Design to Address Issues of Justice

Over the last several years the Electrical and Computer Engineering (ECE) program at Bucknell University has established a four-year 'design thread' in the curriculum. This six-course sequence utilizes a representational approach, having students frame design challenges through diagrams and drawings before starting to implement solutions. The representations students create provide eight lenses on the design process; several of these lenses capture elements of societal implications and social justice. Within the design course sequence, the third-year particularly emphasizes the larger societal and human contexts of design. A challenge in the third-year course has been having engineering students who are acculturated to quantitative and linear methods of problem solving shift their perspectives to address complex societal topics. In the social sciences such topics are usually described textually with rich qualitative descriptions. In an attempt to engage engineering students, the authors have utilized graphical design representations rather than textual descriptions into the course. Such representations better align with engineering epistemology, potentially making the large body of work in the social sciences more accessible to students.

This paper reports on how a particular representation, the system map, has third-year students explore systemic structures and practices that impact design decisions and processes. Students use system maps to identify ways design projects can impact on society in ways that have both positive and potentially negative consequences. Qualitative analysis of student artifacts over five course iterations was used in an action research approach to refine how to effectively integrate system map representations that capture societal issues and address issues of justice. Action research is an iterative methodology that utilizes evidence to improve practice, in this case the improving students' facility with, and conceptions of, the societal impact of engineering work.

This practice-focused paper reports on how system maps can be used in engineering and what supporting practices, e.g. interviews and research, make their use more effective. Ways to utilize system maps specifically, and representations more generally, to connect technical aspects of engineering design to social justice topics and issues are discussed and examples provided to enable others to expand their repertoire of effective practices.

Introduction and Rationale

This paper describes an activity—system map generation—in an engineering design course that was developed to have students better understand the societal and social justice context of their work. The activity was developed as one component of a larger redesign of the course that was intended to achieve the same purposes. The course itself is part of a longer-term curriculum redesign effort intended to graduate engineering students who have a better conception of engineering as both technical and social endeavor than they did previously. In this regard the paper is similar to a *matryoshka* doll where the core activity described in this paper is embedded in larger curricular goals related to placing more emphasis on social justice in an engineering degree program. The use of system maps is described in relationship to these larger goals and structures.

Although the term 'social justice' was coined and used before the professionalization of engineering in the United States, it has never been a priority for engineering education. The belief systems in engineering education as documented by policy reports [1], [2], [3] have evolved from the Mann Report in 1918 [4] which firmly aligned engineering with industry, to the Grinter report of 1955 [5] which placed science as the fulcrum on which engineering was balanced, to more recent reports like the Engineer of 2020 [6] that paints a more nuanced picture of a systemically connected engineer with a wide range of skills that cross management, technology, and science. Yet social justice has never been prominent in these reports. However in the 21st Century a different picture is emerging. As one author wrote in a recent book [7]:

> "*...students are increasingly recognizing that engineering has become the path to a comfortable life, but perhaps not necessarily the path to a good one. My quiet crisis about engineering education is not one of too few engineers, students unprepared for the profession, or our inability to change the education system, but rather one of meaning, of purpose. The questions of purpose arise from the fact that the same factors that have led engineering to be successful are also contributing to negative systemic side effects—on environment, climate, and societal equity—that can no longer be conveniently ignored. The dilemma I perceive is that continuing on our current course leads to success in the short term and potential catastrophe in the long term.*"

The breadth of the issues engineers must address are expanding and their work involves more than technical knowledge, increasingly impinging on the space of the social sciences. As the philosopher of engineering Carl Mitcham [8] points out: "*What Percy Bysshe Shelley said about poets two centuries ago applies even more to engineers today: They are the unacknowledged legislators of the world. By designing and constructing new structures, processes, and products, they are influencing how we live as much as any laws enacted by politicians.*" Technological advances in transportation, distribution, communication, and computing have given rise to a more connected world, which naturally makes the problems engineers address systemic and societal issues. However, the predominant paradigm for teaching engineering at the undergraduate level remains the simplification and decomposition of problems.

There are often conflicting opinions on how to modify degree programs to better prepare students for their future engineering careers, partly because of conflicting beliefs about the purposes and methods of education [9]. For those who believe that current methods are mostly successful, technical preparation takes precedence over contextualizing engineering knowledge in societal contexts. Learning to work within larger social issues occurs on the job and later in one's career. Such prioritization of disciplinary knowledge in the curriculum is, however, often based on a zero-sum calculus that assumes the time spent on societal context is time taken away from core engineering knowledge. There is evidence this perspective is not fully correct [10]. Other perspectives emphasize the need for more professional or transferable skills that will enable engineers to work with others in teams to address societal issues. An example is the KEEN organization [11] that emphasizes entrepreneurship to prepare engineers for a neoliberal capitalist society where the founding belief is that we will continue to technically innovate our way out of dilemmas. These perspectives assume the purpose of education is to prepare a student to contribute to society through their career and societal and justice issues are best addressed by creating a technological "rising tide that lifts all boats". While less common in engineering education, other belief systems emphasize the role of education in addressing societal issues and promoting social justice [12], and emphasizing individual moral and intellectual development such as that exemplified by a liberal-arts curriculum [13]. Debates between these positions can consume considerable oxygen in department meetings, but regardless of one's beliefs about the purposes education should serve, the technologies created by engineers continues to make systems larger and more interconnected.

In this practice-focused paper we report on introducing system maps in a design course to give third-year engineering students practice using tools that enable causal connections of their work to social and global issues. Over the five semesters the course has been taught an ongoing challenge has been having engineering students who are acculturated to quantitative and linear methods of problem solving meaningfully address complex and nuanced societal topics. Most engineering curricula are over-crowded and technically focused, giving students have few opportunities to take courses outside STEM. Research has shown such lack of opportunity causes students who are interested in the social impacts of engineering to lose that interest over the course of an engineering curriculum [14].

The working hypothesis of the efforts described in this article is that engineers will be better able address social justice issues if they learn methods to make societal issues more visible in their work. Under this hypothesis, education should provide tools to perceive social justice issues. Neuroscience has found that perception is not merely a passive reception of sensory data; rather, it is an active process involving the integration of new sensory inputs with existing mental frameworks, memories, and expectations. This integrative function influences how knowledge is acquired; a lack of mental frameworks can act as a barrier in assimilating new information, through selective attention for example [15]. While there are potentially many ways to have students address societal and social justice issues, system maps are chosen over the rich textual and qualitative descriptions more often used in the social sciences since diagrammatic representations align with engineering epistemologies, and system maps have been found to be valuable tools when correctly applied to social challenges [16].

Review of Systems Thinking and System Maps

As used here the term 'system map' refers to a simplified graphical representation of how a complex human-social-technical system behaves. 'System' derives from the Greek root *systema* meaning an organized whole compounded of parts. The positivist scientific revolution with its logical chains of inference that engineering derives from sought to reduce problems into simple parts, and as a result focused less on the whole. Initial work on systems arose in biology since life could not be well described by positivist methods. From its origins in organismal biology system science arose as a synthetic and interdisciplinary field in the 1960's stimulated by advances in computational methods. Since then the ideas of system science have been generalized to organizational [17], [18] and social [16] systems where it is more generally known as 'systems thinking'. Systems thinking is a field that seeks to provide insights on how connections and interdependencies lead to behaviors which are complex and unexplainable from the linear methods and models typically taught in undergraduate engineering education. Systems thinking defines a system as "*…a set of things interconnected in such a way that they produce their own pattern of behavior over time*." [19], p. 4. In other words, a system is defined by relationships which are stable over time rather than the specifics of the entities which form the system.

Systems thinking differs from systems engineering in assumptions about how systems behave. Systems engineering originated in the decades following the Second World War as organizations, operations, and supply chains became larger, more complex, and difficult to manage [20]. Systems engineering defines a system as "*…an integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective*." [21]. Similarly, systems engineering defines itself [22] as "*…an interdisciplinary approach and a means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.*" Systems engineering seeks to predict and control a system for a desired output while systems thinking views top-down control as futile or ineffective. Rather the view that the world is highly interconnected leads to metaphors of nurturing systems and working within, rather than managing, their functionings.

Systems thinking has been integrated into engineering education for some time. Davidz and Nightengale researched how systems thinking develops in engineers [23], finding that experiential learning, individual characteristics, and the environment all play a role. Design approaches like CDIO integrate elements of systems thinking [24] and systems thinking has been considered a separate outcome of engineering programs similar to those mandated by ABET [25]. Systems thinking has been integrated into content-focused courses [26], [27] and there are general calls for engineers to address more systemic and 'wicked' problems [28], [29].

In the larger realm of systems thinking a system *map* is a diagram that identifies the entities which make up a system, called the nodes, and the relationships which connect them, the edges, thus describing how elements of a system relate to each other. System maps are thus a way to represent stable sets of (ideally causal) relationships that define what a system does and how it works. Research has found [17] that despite being highly variable in their makeup, the ways that systems behave have common features and exhibit a relatively small set of stable behaviors. Systems maps are diagrammatic representations that visually represent the relationships by which a system performs its functions and given insight into these behavior patterns. In social systems system maps have been widely used to provide insights into why issues persist despite good-faith attempts to address them [16]. By creating simple representations of how the interactions of different agencies, organization, initiatives, and populations lead to stable dynamics that resist change, system maps are used to inform interventions, guide funding efforts, and build more effective partnerships. System maps also give students new insights into their own roles in existing systems. Undergraduate engineering students typically don't notice the systems they are part of because (1) they live in them – the system is simply "the way things are", and (2) systems tend to be stable, that is change slowly over time. By definition functioning systems exhibit stability and it is only when systems break down or don't behave in expected ways that they become objects of attention.

Integrating System Maps into a Design Course

As discussed previously, the educational goal related to social justice was to provide students tools and experience in how to better understand the systemic impacts of engineering solutions in ways that are causal and rigorous. The authors undertook a multi-year effort to introduce system map representations as part of a third-year engineering design course. The design course is required of students in both the electrical and computer engineering degree programs of a single department at a rural liberal arts institution. The program has approximately 100 students across all four years of the curriculum. Approximately 60% of the students are in the electrical engineering program and 40% are in the computer engineering program; both programs are informed by the liberal arts mission of the university. The course credits required for a degree are distributed roughly equally (25% each) in four categories: science & math, engineering science, design & technical electives, and open electives. Compared with most other ECE degree programs in the United States there are fewer prerequisites, more design, and more open electives.

There are six required design courses in the curriculum: two each in the first and last years, and one each in the second and third years. All department-taught design courses view design as composed of eight overlapping perspectives as shown in Figure 1 below. Each perspective has a set of written or graphical representations associated with it to help students learn to address that aspect of design. The first year courses are introductions to design in engineering and ECE respectively that cover all perspectives of Figure 1, but without much depth. The second year course focuses on the "build responsibly" and "improve performance" aspects to give students skills in electronic fabrication. The third-year course discussed here focuses on problem identification and context, covering "help people & the planet", and "embrace the context" and also emphasizing "choose useful functions" and "design transparently". The two courses in the senior, capstone sequence cover all eight aspects. The system map representation discussed here aligns with the "embrace the context" perspective.

The third-year course is ½ credit, corresponding to two credit-hours. Initially the course was designed as a miniature introductory version of the two-credit senior capstone course to prepare students for the year-long capstone sequence. To shift the focus to address more societal issues an action-based research [30], [31] approach was used over five iterations of the design course. Action-based research is used to improve or change practices by a sequential and iterative series of actions, the effects of which are determined through subsequent research and critical reflection. An action research approach was chosen due to its alignment with the goal of making students more aware of the relation of engineers to social justice; action research has a participatory character, democratic impulse, and can simultaneously contribute to both generalized understanding and social change [32]. How these are enacted is described below.

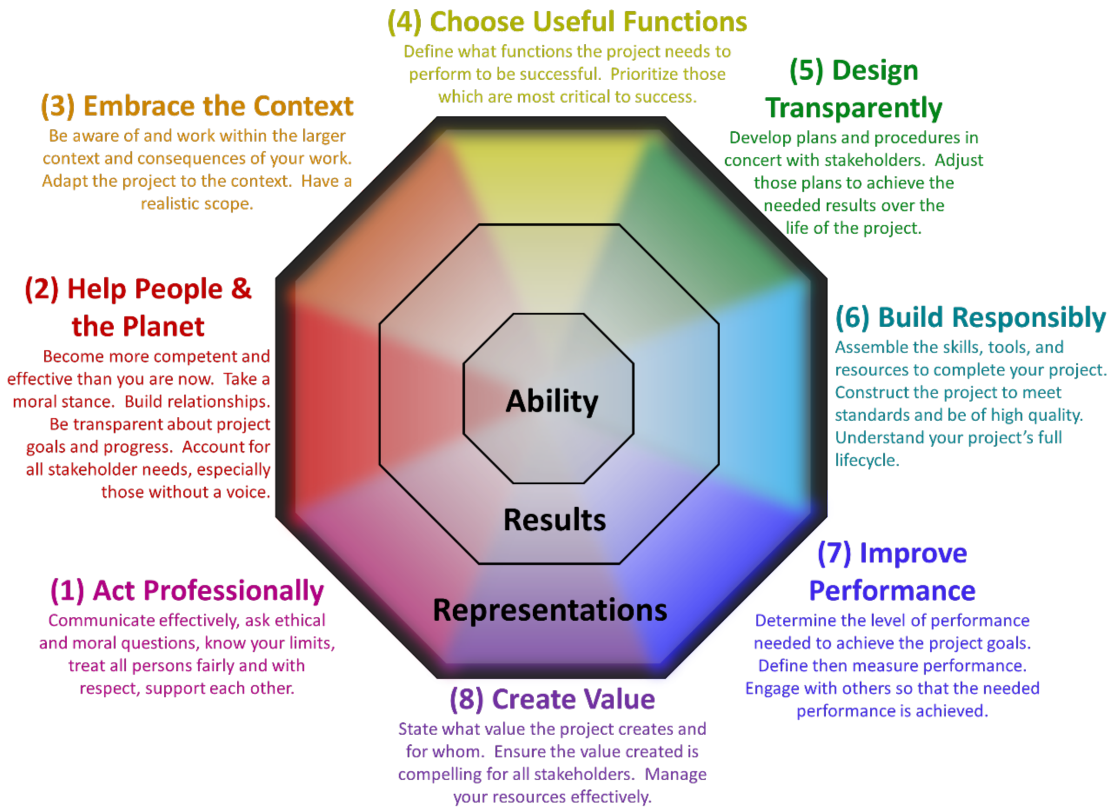

Figure 1: Eight design perspectives supported in the six course design sequence in the ECE curriculum at Bucknell University.

Method and Actions

The focus of the 'miniature capstone' course was observed to be too technology-focused, with students seeing the learning outcomes as applying prior technical knowledge to a prototype solution. Action research was chosen to shift the learning towards developing systemic perspectives on larger societal challenges and social justice. This was accomplished by developing graphical and written representations [33] for perspectives (2)-(4) in Figure 1 to enable students to better perceive and address societal issues impacting upon their design projects.

Methodologically a combination of primarily first-person with some elements of second-person action research was used. The course was either co-taught or engaged an embedded ethnographer over the five semesters the study was performed and all of the team engaged in critical reflection. The course instructors recognized at the outset of the course that the 'capstone in miniature' format was not suitable for the desired goals of increasing student understanding of social context and justice in the design course. The instructors took the critical stance that the technological focus of engineering and more career-oriented interventions would not suffice for developing systemic understanding of the human and social systems in which engineering projects are embedded. This first-person stance allowed us to look at the artifacts students created as well as their reflections during and after the course to gain a better understanding of the relative importance students placed on different course elements and their relation to our teaching practices. The student artifacts that informed our reflections on the course are described in Table 1.

Table 1: Artifacts analyzed for action research

Artifact	Description
Team Design Report	Report written in three iterations with substantive feedback following each version.
Individual E-portfolio	Used Campbell's 'hero's journey' template to capture key aspects of the design experience.
Representations	Individual textual and graphical representations of the team design, e.g. system map, block diagram, flow diagram, NABC [34], problem description, etc.
Reflections	Weekly individual reflections on Basecamp [35] are responded to by the instructors.
Perusall	Student comments and annotations on readings using the Perusall system [36] are captured and read regularly.
Zotero	Students post research articles weekly onto a shared Zotero account. The suitability of articles and any annotations and notes are analyzed.

Reviews of the artifacts and critical review of the student reflections and our responses led us to recognize our own biases towards implementing technological solutions limited the time we allowed students to delve into human and social aspects of design. The embedded ethnographer was critical in helping shift this aspect of the course. These insights were also informed by a student-led after-action review following the subsequent year-long capstone course in which students reflected on the overall design sequence for a three-hour period at the end of each academic year. During this review instructors allowed the students to lead the discussion and served as scribes, writing down student thoughts and observations on classroom whiteboards. Students were asked to help redesign elements of the design sequence they found less than effective. After these activities the instructors met for several sessions over the summer or winter breaks, and devised changes that would be implemented the next semester.

Since the goal was to improve students understanding of social and human contexts of engineering, particularly related to issues of justice, the critical reflection resulted in a number of changes. The most significant of these, and the one that had the largest positive impact, was expanding the focus on system maps and the supporting activities required to do this. Figure 2 shows a timeline of when different elements of the course related to system maps were introduced over the five-semester duration of the action research project; these are discussed below. Note that in one semester, spring 2022, the course was assigned to other faculty and results are not available. The modifications made to the course over the five-semester duration of the action research project related to providing students additional perspectives on larger societal issues related to justice are described below. While the practical mechanics of teaching required multiple changes to course timing, organization, and content, below we focus on those that were the most consequential changes to shifting students perceptions towards justice.

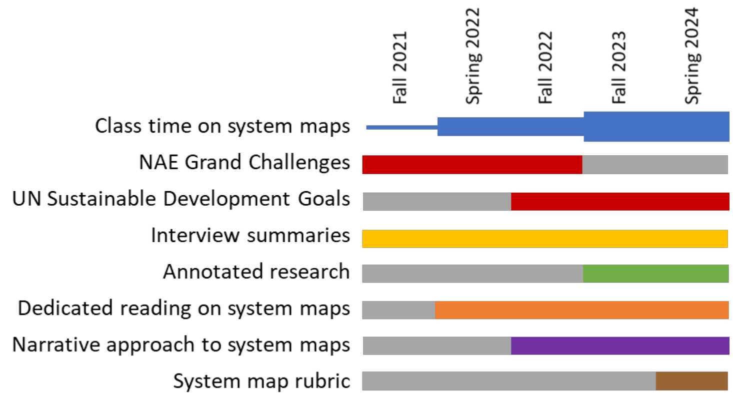

Figure 2: The timeline above illustrates changes in the 3rd-year design course over the period of the action research project. Grey represents the element of the course was not present, and colors when the element was included.

Shift in Focus: The first modification was to shift the course from 'capstone in miniature' to focus it more on choosing appropriate problems. We observed that covering all eight perspectives of Figure 1 introduced too many representations. Students reflected they had little opportunity to engage with the various representations in-depth as evidenced by reports being unfocused and rambling. Classroom observations showed that most students saw the representations as a form of homework rather than as tools to help inform their design process. The shift to emphasize problem identification was accomplished several ways. First, we shifted from the National Academy of Engineering Grand Challenges [37] used previously to having students choose a United Nations Sustainable Development Goal (UNSDG) [38] since UNSDGs are more focused on social issues than technological solutions. This transition is shown in Figure 2, and for one semester students could choose from both Grand Challenges or UNSDGs. Initially teams of 3-4 students each chose a challenge or UNSDG to work on, but this resulted in a wide range of topics that was difficult to provide in-depth support for. To create a more coherent set of projects and better alignment between students' effort in later iterations of the course, students first read about UNSDGs on Perusall [36], then a class period was devoted to having students devise a democratic voting process to choose a single goal the class would work on.

To focus more on problem identification, the scope of the class was narrowed over the five semesters. From covering each of the eight design perspectives of Figure 1 in the 'miniature capstone' format the emphasis of the course shifted to spend more time on 'help people & the planet', 'embrace the context', and 'choose useful functions'. Student reflections on Basecamp prior to this shift indicated they lacked time to sufficiently explore aspects of problem identification. This was reflected in both the quality of their representations, their report, and little emphasis put on problem identification in their e-portfolios which tended to focus on the results of the project. The number of different representations introduced in the course dropped from about a dozen to six. Because observations of student work showed they could transfer knowledge from the second-year design course that focuses on the 'build responsibly' and 'improve performance' perspectives these perspectives were de-emphasized over time.

Additionally rather than undertake two iterations of the design project the course focused a single minimum viable product (MVP) iteration. This created the time needed to go more in-depth on social impact. In our own critical self-reflection the time pressures of this format manifested as feelings of stress and creating assignments focused on students covering material. Shifting to focus on a smaller number of lenses reduced this time pressure, enabling us to slow down the course, engage more with students, and better address individual student needs.

System Maps: The largest and most significant change was integrating system maps, described previously, into the design course as a representation that could capture social realities and relate them to technological interventions student teams could design. While system maps were introduced into the first iteration of the course as one of 12 representations, we quickly learned by analyzing the depth, validity, and further use of the system map in the report and e-portfolio that students need more time with this representation. Over the five semester action research project we shifted from spending half a class period in formal instruction on system maps (using a flipped classroom modality) to five class periods as shown in Figure 2. Given that this class is the first time that students address complex, rather than simple and complicated problems amenable to linear solution methods, a considerable amount of experimentation on effective methods was needed to allow meaningful integration of system maps. The approaches taken are described below.

Initially system thinking and system maps were introduced to students through excerpts from several books [16], [19], however it was found from student reflections and comments on the readings on Perusall that excerpted chapters were not appropriate for integration into an undergraduate design course given the time constraints. This was reflected in our emotional state as an unresolvable tension between the depth of learning and the time allotted for activities. To eventually address this tension we drew from these sources to create a short (approximately 20 page) two-part reading on system maps and systems thinking [39] that was more approachable for students (see Figure 2). To make concepts such as balance and reinforcing loops, delays, and inverse effects approachable for students, example system maps were framed through a professor's mental models about grading and various attempts to change their course was managed. Numerous examples of system maps were provided. The readings are supported using existing TED® talks on complexity and complex systems.

Based on critical reflection and analysis of student representations and reports, in early iterations of the course students had a rather transactional and deterministic perspective on system maps. The maps were deterministic in that they described a simple chain of events that could be explained linearly rather than as a series of causal loops that led to static behavior patterns. This likely arose since most problems attempted by students in prior classes were amenable to the linear solution methods addressed in these courses. The maps were transactional in they were seen as another homework assignment needed to earn a grade in the class rather than as a useful tool to consider larger contextual aspects of an engineering design issue. The transactional view arose largely due to insufficient time spent explaining the use and development of system maps. The dedicated reading described above helped with this issue as did increasing the amount of class time spent from half a course-hour to five course hours. Later iterations of the course starting in Fall 2022 (Figure 2) also explicitly introduced narrative modes of thinking and contrasted them with the logico-rational mode typically used in engineering courses. These two modes of thought were introduced by Bruner [40] who highlighted that any situation too complex for a logical solution is explained through the use of stories. Our own understanding of the role of system maps has changed as a result of making changes to the course. Rather than seeing system maps a topic or content to be covered, they have become an exercise in thinking causally, drawing inferences, and synthesizing student research in an understandable and easy-to-communicate format. This view has allowed us to engage more deeply in the process of creating system maps rather than viewing them as an 'output' of the design process.

To teach students how to frame socio-technical challenges narratively Bruner's framework of '*characters* in *action* with specific *intentions* in *settings* using *means*' was used. In Bruner's framing conflicts between the five italicized elements form the basic elements of narratives and these also apply to issues of social justice. In class students analyze an article about a socio-technical system related to the chosen UNSDG then try to reframe it into a narrative, identifying tensions and interactions, as an introduction to system mapping. Generally students found this exercise to create some cognitive dissonance, which was intended by the instructors in order to take them out of their comfort zone and explicitly signal that the course was different than other courses they had taken so they would need to adopt different strategies to be successful. Following the narrative introduction two additional class periods are spent reading about system and developing initial system maps to identify issues related to the UNSDG. Two final days are used for several rounds of revision of student system maps.

Research: Because most engineering students have not formally encountered ways to conceive of larger social systems in their studies and their knowledge of external events varies widely, over the various iterations of the course the instructors found that it was important to have students perform independent research. Initial analysis of team reports and student e-portfolios indicated students were not always familiar with how to support claims in their thinking and writing. Student research consisted of both reading relevant articles and conducting interviews with experts. Interviews are based on the book *Talking to Humans* [41]. Students do relatively few interviews, about three or four over the semester. More emphasis is put on reading, including journal articles, well-researched magazines like *The Atlantic*, online sources such as *The Conversation* (e.g. [42]), and sections from books. How to do research and why it was important is introduced during a class period by a research librarian, and students then perform the research as part of the time they put into their project outside of class. Since each class picks a different UNSDG and each team works on a different aspect of that goal, students are responsible for choosing relevant articles; generally they are quite adept at doing so as judged by analysis of the articles they choose and the annotations and notes they make in Zotero [43]. In Fall 2023 (Figure 2) formal graded assignments were introduced where students do a weekly annotated summary of articles in a shared class Zotero folder. This assignment stretches throughout the whole semester.

Feedback: Finally, it was found through trial-and-error responses to individual student reflections that students could benefit from more formal feedback on their system maps. For experts system maps' quality often has "I know it when I see it" characteristic, but such feedback is not helpful to novices. While books on systems thinking [16], [19] do describe elements of successful system maps, there is not sufficient time for students to gain sufficient experience to develop evaluative skills. Initially faculty provided in-the-moment guidance during days in class in which students worked on their system maps, but the feedback was somewhat *ad-hoc*. In the most recent iteration of the course the instructors developed a simple rubric drawing from literature on system thinking and system mapping to be able to provide more direct and actionable to feedback. The current version of the rubric is shown in Table 2. While the impact of the rubric has not yet been determined, initial results will be available by the time the revised paper is submitted. As shown in Table 2, system maps are broadly qualified on the meaning they convey and the extent to which their structure follows conventions.

Table 2: Rubric for System Maps

Criteria to Determine Usefulness of System Maps			
Narrative and Meaning	**Little Evidence**	**Some Evidence**	**Mostly Evident**
Causality – Is there a clear cause-and-effect connection between the nodes of the system map?			
Confirmability – the system map can be externally validated and aligns with reality; nodes and/or edges have citations.			
Credibility – is the situation described on the system map realistic, does it make sense internally, does it have a self-consistent logic?			
Narrative – the system map explains issues, giving insights into how the issues persist and how they might be addressed.			
Structure and Layout	**Lacks**	**Some**	**Has**
Loops instead of Linearity – the system map expresses behavior as loops rather than in a linear structure.			
Archetypes Identified – the loop structure of the system map is mapped to archetypes that describe behaviors.			
Behavior Identified – the reinforcing and balancing loops and delays are marked and make sense in the context of the problem.			
Time Dependent –Behavior over time is shown and describes the dynamics of the issue being addressed.			

Results

These changes, made iteratively over time, have resulted in a significant change in students' ability to frame issues that are deeply embedded in societal contexts. One way we retroactively examined changes was to plot the size of the system maps students developed in the first iteration of the map they submitted. Taking the average number of nodes and edges on system maps included in student reports over the four semesters for which data is available a trend towards larger and more complete maps with more is evident as shown in Figure 3.

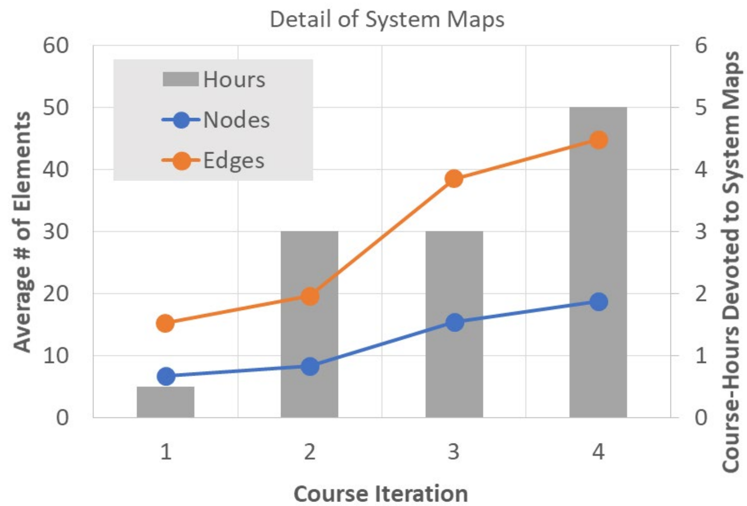

Figure 3: The change in the average size and detail of system maps over the four completed iterations of the course as measured by number of nodes and edges. The grey bars show the number of course-hours devoted to instruction on system maps.

Beyond increased complexity, the iterative changes to the course have resulted in better quality system maps as determined by rubric scores. While as discussed previously 'quality' is difficult to define, the rubric in table 2 enabled analysis. Initial results indicate that the ratings of causality and credibility have the most validity as proxies for the quality of a system map, but insufficient data is available to support this as a finding.

The way students use system maps has also changed. As mentioned previously, initially system maps were seen in a transactional way as another assignment needed to earn a course grade. The changes made have both encouraged students to engage more deeply with social contexts, but also change their view of context in a dynamic way throughout the design process. In Figure 4 below three system maps are seen that correspond to how a single team's system map evolved over time in the Fall 2023 semester. The specifics of the maps are not important, rather the interesting aspect is how the structure changes. In this example, which was fairly typical in later iterations of the design course, initially the team sees a large problem space with very many possible factors affecting the domain they are working in; in this case mental health issues among homeless populations. As time goes on, student teams simplify the system map, focusing in on a particular aspect of the system to intervene in. The caption of Figure 4 provides data on the size of the network determined by nodes or edges, the clustering coefficient which measures the degree to which nodes in a network tend to cluster together, and the network density determined by the ratio of the number of edges present to the number of possible edges which gives an idea of how closely knit the network is. Over the course of the semester the number of nodes and edges drops significantly (by a factor of three), the global clustering coefficient rises significantly showing tighter interconnection, while the network density also increases by approximately factor of three showing tighter interconnection. These trends indicate that a process takes place in which system map representations encourage students to initially broadly explore social issues and over time decide on a smaller set of social relationships on which to focus their design project.

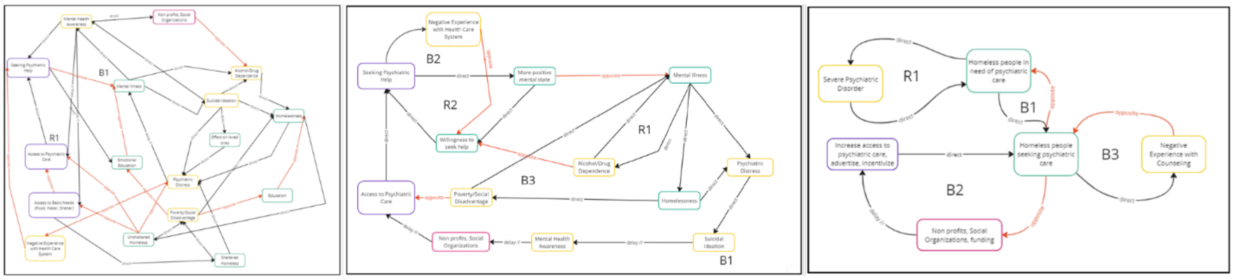

Figure 4: Three snapshots of a student team system map at approximately the 5th, 10th, and 15th week of the course. The number of edges drops from 28 to 20 to 9 and nodes decrease from 17 to 13 to 6. The global clustering coefficient changes from 0.032 → 0.040 → 0.200 while the network density changes from 10.3% to 12.8% to 30%.

Discussion and Practice

At one level it is not surprising that improvements to the system maps created by student teams occurred over the course of this action research project. Much of the improvement was likely due to providing more time and support in developing system maps in class. System mapping, however, provides an approach that is both accessible to engineering students with pre-conditioned epistemological stances that our observations suggest can also significantly addresses 'the culture of disengagement' [14] in engineering programs. Below we discuss some of the practical aspects of implementation, but first it is important to note the limitations. This is a single representation used in a partial-credit engineering design course. The goal is not to train engineering students as social scientists, but to explore practical design representations that expand student understanding of the importance of societal contexts and issues of justice that arise between different groups within a social system while meeting time constraints.

Despite attempts to improve how students develop system maps, the shift to focusing on problems before considering solutions is a difficult one for students. Observations in class supported by reflections and comments in student e-portfolios show that students tend to gravitate to discussing solutions as they are identifying issues in a social system. As faculty see *solving* problems as a core element of being an engineer [44], this tendency is deeply embedded in students' epistemological stance. Some of this tendency may be due to the broad scope of problems as defined in the UNSDGs. In class it was important to continually remind students to focus on problems rather than jump to solutions and help them narrow down the scope of problems based on their own interests. Guidance was given on thinking about which problems are amenable to solution by a given engineering discipline.

The form of knowledge represented by system maps—which is holistic, highly relational, and deeply contextualized in policy and community—can be foreign to the epistemological stance students have learned in other engineering courses. That is the way such knowledge is structured differs from the emphasis engineering puts on problem decomposition and simplification [45]. Making this shift can be difficult for some students, however our experience has been that while graphical representation of knowledge helps students better understand these differences, explicit instruction plays an important role as well.

We have similarly found that it helps to highlight the differences between the forms of knowing used in engineering and those used in other domains by using narrative as described above. Students all have experience with stories, and some, when given permission, will deeply engage in story-telling. System maps can be thought of as the plot of a story, and populating the diagram with real or fictional people to illustrate the human aspects of the issues both helps make the representation more real for the students and can help find logical inconsistencies since narrative forms of explanation are extremely powerful for understanding 'why' questions.

Despite using an engineering-adjacent representation that is essentially a graphical form of coupled differential equations, some students think that societal issues related to justice and resource use lie too far afield from their view of engineering to be relevant. Realistically one should expect this position since this mental stance can be fairly deeply ingrained and closely tied to a student's identity. Since identity is contextual, the techniques described above to make a space in an engineering classroom that is purposefully different are helpful. Another method is to tie system maps to actual engineering practice. Books that describe system maps as helpful tools [46] can help doubtful students see the relationship of tools that provide insight into context to engineering practice.

Conclusion

In conclusion, this paper has described use of a particular graphical representation—system maps—as an effective and relatively time effective method to introduce discussions of social justice into engineering design classes. The underlying argument for using a system map representation is that to be able to address issues of social justice engineers need to gain experience in perceiving those issues, not as simple mandates, but in the full complexity of social relationships. System maps make relationships visible. As presented here, groups of students develop system maps based on research they do into a United Nations Sustainable Development Goal. We have shown that an investment of five days on system maps and one on research allow students to develop nuanced maps that can guide intentional and well-thought-through technical intervention. While students develop these maps over five course-hours—including associated readings, in-class, and homework assignments—early in the third-year design course, they continue to work on and refine their maps as they develop a technological intervention than can address a small part of the problem space. The evidence collected, from student artifacts, written reflections, class observations, etc. (see Table 1) points to system maps as an effective intervention that lies at the intersection of design and social justice.

From the faculty perspective one of the most valuable aspects of having student teams create system maps is the side conversations that occur. As mentioned previously, the course is taught in a flipped classroom modality so students work on their system maps during class, enabling rich conversations between faculty members and the design teams. These conversations serve as opportunities to illustrate to students how their engineering work recreates existing social issues.

For example, one team wanted to build a system to test water in developing countries that relied heavily on advanced infrastructure. Using the team's system map the instructors pointed out that the resulting imbalance of power and control recreated colonialism. Another time the system map illustrated to students how their intervention, an app to find empty parking spots on campus in real time, could lead to unsafe behaviors. It is these individual conversations, supported by the system map as a conversational artifact, that allows many of the historic issues of justice to be illuminated.

This work was supported by the National Science Foundation under award EEC-2022271. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Bibliography

[1] A. Akera, "Setting the Standards for Engineering Education: A History [Scanning Our Past]," *Proc. IEEE*, vol. 105, no. 9, pp. 1834–1843, Sep. 2017, doi: 10.1109/JPROC.2017.2729406.
[2] B. Seely, "'Patterns in the History of Engineering Education Reform: A Brief Essay,'" in *Educating the engineer of 2020: Adapting engineering education to the new century*, Washington D.C.: National Academcy Press, 2005, pp. 114–130.
[3] R. A. Cheville, "A Century of Defining Engineering Education," in *2014 ASEE Annual Conference & Exposition*, Indianapolis, 2014.
[4] C. R. Mann and M. Press, "A Study of Engineering Education," Carnegie Foundation for the Advancement of Teaching, Boston, 1918.
[5] Grinter Report, "Report on evaluation of engineering education (reprint of the 1955 report)," *J. Eng. Educ.*, vol. 93, no. 1, pp. 74–94, 1994.
[6] G. W. Clough *et al.*, *The Engineer of 2020: Visions of Engineering in the New Century*. Washington, DC: National Academcy Press, 2004.
[7] R. A. Cheville, *Becoming a Human Engineer: A Philosophical Inquiry into Engineering Education as Means or Ends?* 2021.
[8] C. Mitcham, "The True Grand Challenge for Engineering: Self-Knowledge," *Issues Sci. Technol.*, vol. 31, no. 1, 2014.
[9] M. S. Schiro, *Curriculum Theory: Conflicting Visions and Enduring Concerns*. Thousand Oaks, CA: Sage, 2012.
[10] S. B. Nolen, E. L. Michor, and M. D. Koretsky, "Engineers, figuring it out: Collaborative learning in cultural worlds," *J. Eng. Educ.*, vol. 113, no. 1, pp. 164–194, Jan. 2024, doi: 10.1002/jee.20576.
[11] Kern Family Foundation, "KEEN Engineering Unleashed." 2019. Accessed: Feb. 01, 2019. [Online]. Available: https://engineeringunleashed.com/
[12] D. M. Riley, "Employing Liberative Pedagogies in Engineering Education," *J. Women Minor. Sci. Eng.*, vol. 9, no. 2, pp. 30–32, 2003.
[13] L. L. Bucciarelli and D. E. Drew, "Liberal studies in engineering – a design plan," *Eng Stud.*, vol. 7, no. 2–3, pp. 103–122, 2015.
[14] E. A. Cech, "Culture of Disengagement in Engineering Education?," *Sci. Technol. Hum. Values*, vol. 39, no. 1, pp. 42–72, 2014, doi: 10.1177/0162243913504305.
[15] J. Driver, "A selective review of selective attention research from the past century," *Br. J. Psychol.*, vol. 92, no. 1, pp. 53–78, 2001, doi: 10.1348/000712601162103.
[16] D. P. Stroh, *Systems Thinking For Social Change: A Practical Guide to Solving Complex Problems, Avoiding Unintended Consequences, and Achieving Lasting Results*. White River Junction, VT: Chelsea Green Publishing, 2015.

[17] P. Senge, *The Fifth Discipline: The Art & Practice of The Learning Organization*. New York: Doubleday, 2006.
[18] L. B. Barnes, *Organizational Systems and Engineering Groups*. Cambridge, MA: Harvard University Press, 1960.
[19] D. H. Meadows, *Thinking in Systems: A Primer*. White River, Vermont: Chelsea Green Publishing, 2008.
[20] C. West Churchman, *The Systems Approach*. New York: Dell, 1984.
[21] Department of Defense Systems Management College, *Systems Engineering Fundamentals*. Fort Belvoir: Defense Acquisition University Press, 2001.
[22] C. Haskins, K. Forsberg, M. Krueger, D. Walden, and D. Hamelin, “Systems engineering handbook,” in *INCOSE*, 2006. doi: SP-610S.
[23] H. L. Davidz and D. J. Nightingale, “Enabling systems thinking to accelerate the development of senior systems engineers,” *Syst. Eng.*, vol. 11, no. 1, pp. 1–14, 2008, doi: 10.1002/sys.20081.
[24] *Rethinking Engineering Education*. Boston, MA: Springer US, 2007. doi: 10.1007/978-0-387-38290-6.
[25] J. Froyd, L. Pchenitchnaia, D. Fowler, and N. Simpson, “Systems thinking and integrative learning outcomes,” in *2007 Annual Conference & Exposition*, 2007, pp. 12–1340. Accessed: Mar. 31, 2024. [Online]. Available: https://peer.asee.org/systems-thinking-and-integrative-learning-outcomes
[26] H. Arndt, “Enhancing System Thinking in Education Using System Dynamics,” *SIMULATION*, vol. 82, no. 11, pp. 795–806, Nov. 2006, doi: 10.1177/0037549706075250.
[27] Y.-L. Han, K. Cook, G. Mason, and T. R. Shuman, “Enhance Engineering Design Education in the Middle Years With Authentic Engineering Problems,” *J. Mech. Des.*, vol. 140, no. 122001, Sep. 2018, doi: 10.1115/1.4040880.
[28] R. Graham, *The Global State of the Art in Engineering Education*. Cambridge, MA, 2018.
[29] G. Mahavan, *Wicked Problems: How to Engineer a Better World*. New York: W. W. Norton & Company, 2024.
[30] M. Walker and S. Loots, “Transformative Change in Higher Education through Participatory Action Research: A Capabilities Analysis,” *Educ. Action Res.*, vol. 26, no. 1, pp. 166–181, 2018.
[31] G. M. Bodner and M. Orgill, *Theoretical Frameworks for Research in Chemistry/Science Education*. New York: Prentice-Hall, 2007.
[32] K. Kinsler, “The utility of educational action research for emancipatory change,” *Action Res.*, vol. 8, no. 2, pp. 171–189, Jun. 2010, doi: 10.1177/1476750309351357.
[33] T. J. Moore, R. L. Miller, R. A. Lesh, M. S. Stohlmann, and Y. R. Kim, “Modeling in engineering: the role of represntational fluency in students’ conceptual understanding,” *J. Eng. Educ.*, vol. 102, no. 1, pp. 141–178, 2013.
[34] C. R. Carlson and W. W. Wilmot, *Innovation: The Five Disciplines for Creating What Customers Want*. New York: Crown Business, 2006.
[35] “Project management software, online collaboration,” Basecamp. Accessed: Apr. 24, 2023. [Online]. Available: https://basecamp.com/
[36] “Perusall | Increase student engagement, participation, and collaboration.” Accessed: Apr. 24, 2023. [Online]. Available: https://www.perusall.com
[37] Grand Challenges for Engineering Committee, “Grand Challenges for Engineering,” National Academy of Engineering, Washington, DC, 2008. [Online]. Available: http://www.engineeringchallenges.org/Object.File/Master/11/574/Grand
[38] United Nations, “United Nations Sustainable Development Goals,” United Nations. [Online]. Available: https://sdgs.un.org/goals
[39] R. A. Cheville, “System Maps.” Google Drive, 2024. [Online]. Available: https://drive.google.com/file/d/1PXJtUZBMY-CeZL0UMkGur9gU5H5i5uEP/view?usp=drive_link
[40] J. Bruner, *Actual Minds, Possible Worlds*. Cambridge, MA: Harvard University Press, 1987.
[41] G. Constable, *Talking to Humans*. Self published, 2014.

[42] J. Dernbach and S. Schang, “The US committed to meet the UN’s Sustainable Development Goals, but like other countries, it’s struggling to make progress,” The Conversation. Accessed: Sep. 20, 2023. [Online]. Available: http://theconversation.com/the-us-committed-to-meet-the-uns-sustainable-development-goals-but-like-other-countries-its-struggling-to-make-progress-212585
[43] Center for History and New Media, “Zotero Quick Start Guide.” [Online]. Available: http://zotero.org/support/quick_start_guide
[44] A. L. Pawley, “Universalized Narratives: Patterns in How Faculty Members Define ‘Engineering,’” *J Eng Educ*, vol. 98, pp. 309–319, 2009.
[45] D. J. Snowden and M. E. Boone, “Leader’s Framework for Decision Making - Harvard Business Review,” *Harv. Bus. Rev.*, 2007, [Online]. Available: http://hbr.org/product/a-leader-s-framework-for-decision-making-harvard-b/an/R0711C-PDF-ENG
[46] W. Larson, *An Elegant Puzzle: Systems of Engineering Management*. San Francisco: Stripe Press, 2019.