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Navigating Design – Maps and Dead Reckoning

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This paper looks at engineering design education through an analogy of maritime navigation. The analogy of a journey to a destination while avoiding perils along the way provides insights into the design process. In modern maritime navigation vessels rely on maps and instrumentation to accurately determine their position as they navigate to a known destination. The analogy in design is defined specifications that provide details on the desired endpoint and project metrics that mark milestones on the journey. If the main goal of design is viewed as a product this is a valid analogy. However, some design projects are less specified, and the ending destination may be envisioned in a general sense without being able to be specified or located. Projects that intersect broader societal needs—design for social justice or design embedded in communities—are more often of this form. Prior to accurate maps and navigational technology mariners utilized dead-reckoning—a heuristic-based method—to make long ocean voyages. Rather than accurately locating oneself with respect to a defined destination dead-reckoning relies on three heuristics: know your starting direction, hold a steady course and estimate the distance traveled, and know when you get near your destination.

This paper analyzes student artifacts from three courses in a five-course design sequence at a mid-Atlantic private university to explore how students transition from specification-based design to being able to navigate ill-defined design challenges in a heuristic-driven manner. By reducing scaffolding over time, the three design courses enable students and teams to develop key skills needed for 'design navigation' in the space where engineering intersects broader societal needs. Key aspects include developing student agency, scaffolding design-relevant skills, and emphasizing problem scoping.

Introduction

In this paper navigational analogies are used to understand learning in design courses. Unlike courses that are designed to teach engineering content and topics, design courses have several key differences [1]. Topical courses tend to emphasize disciplinary knowledge and assess student learning through exams and problem sets; methods that rely on having a "right" answer. This emphasis on acquisition of fixed knowledge can lead to topical courses being viewed as "gatekeepers" by faculty. It can be difficult to incorporate material outside of disciplinary boundaries in gatekeeping courses since by definition they focus on content related only to a specific topic. In contrast, design courses may offer more open-ended problems and projects. The open-endedness of design courses in turn requires the use of skills such as communication, teamwork, and systems thinking if design processes are to be successfully negotiated [2]. Without "right" answers, design courses incorporate decision-making and uncertainty.

While all endeavors have some level of uncertainty or risk, engineering develops technologies to minimize such risks. In maritime navigation, for example, technologies developed over centuries minimize risks. From the development of accurate clocks and compasses (Coulomb's Law was a side-effect of seeking a maritime prize) to modern satellite navigation systems there has been an increasing emphasis on accuracy both in positioning and in maps. Modern navigation emphasizes instruments, accuracy, and maps to enable voyagers to plot the safest and most efficient route between two known destinations. Before modern technologies enabled map-based navigation, however, indigenous peoples developed alternative navigational methods, commonly known as dead-reckoning. These will be discussed in greater detail subsequently, but in essence dead-reckoning is a heuristic-based method. Rather than accurately locating oneself with respect to a defined destination dead-reckoning relies on three expert heuristics: know your starting direction, hold a steady course and estimate the distance traveled, and know when you get near your destination.

These two navigational analogies provide relevant insights for engineering design education. Map-based navigation corresponds to design through well-defined specifications that provide details on the desired endpoint and project metrics that mark milestones on the journey. In education this analogy aligns with outcome-based models that are currently prevalent due to ABET [3]; know what learning outcomes students are to achieve, use effective methods, and measure attainment. If the main goal of design or education is viewed as a product this map-based analogy makes sense. However, not design projects exist on a spectrum of specificity – that is the ending destination may be envisioned in a general sense without being able to be specified or located. Projects that intersect broader societal needs—design for social justice or design embedded in communities—are often of this form since they are highly impacted by local contexts [4]. Dead-reckoning may be seen as loosely aligning with divergent phases of design while map-based navigation aligns with convergent phases [5]. In education dead-reckoning can be loosely associated with educational pathways [6] and ecological and complexity models of education [7], [8] that draw on practices of enactivism [9].

The purpose of this paper is to explore the insights these navigational analogies provide into student learning and choice of course structure in a sequence of design courses. In other words, how can using these two navigational analogies to interpret student work provide insights into teaching engineering design? How does viewing design from the perspective of these analogies inform how design is taught and assessed? For example, while outcomes-based frameworks push towards map-based models and "destinational certainty" if design were based on a dead-reckoning framework what might the results be?

The use of analogies flies, to some extent, against the epistemological stance of engineering, which historically adopts more rational, positivist, and empirical perspectives [7]. However, as the issues engineers address are increasingly seen as becoming more complex—a phenomena captured by terms such as convergent [10] or transdisciplinary—the author's opinion is that an expansion of engineering ways of thinking will be needed. In terms of positionality, the author is a faculty member in an electrical and computer engineering (ECE) degree program at a liberal arts university in the mid-Atlantic region of the United States. My perspective is shaped by my academic background, professional experiences, and personal values. Having experiences in large public land grants as well as private research and primarily undergraduate institutions has led to an institution-agnostic view of engineering education. Spending time at the National Science Foundation facilitated this divorce from institutional priorities, shifting my perspective to understand education's role in supporting larger social systems. My views on engineering education were also shaped by growing up outside the US under a state capitalism [11] or quasisovereign governance [12] model. These experiences provide perspectives that help support counter-narratives to those of neoliberalism and free market capitalism. Such narratives play important but often invisible roles in how engineering education is constituted and managed [8], [13], [14]. Life experience has also informed my stance toward environmental and sustainability issues, which I place paramount in terms of moral values, driving my stance on engineering ethics. While these experiences create biases, their impact is mitigated by seeking to actively engage with diverse perspectives, being methodologically reflexive, and adopting established frameworks.

Background, foundation, and definitions

As discussed in the introduction, this paper looks at engineering design learning through two different navigational analogies – map-based and dead-reckoning. Analogies are often used in science and engineering since they provide a bridge from familiar concepts to new ways of understanding [15], [16]. but have both advantages and pitfalls. Similarly in education analogies can facilitate better understanding of new concepts [16] by helping students see deep structural connections. The goal in this paper is similar – to better understand student design experience through contrasting lenses. Analogies are used in design education [17], [18], [19]. Similarly designers use analogies in product development [20], [21], [22].

As with any method, analogies offer both advantages and pitfalls. Analogies can help bridge the gap between abstract concepts and familiar ideas, in this case making insights into learning design more accessible. Similarly, as in the case of Kepler, analogies can inspire new ideas and methods by linking seemingly unrelated domains by facilitating cross-domain knowledge transfer which encourages the interdisciplinary collaborations called for in convergence [10]. Analogies also can make communication between individuals from different backgrounds or holding different beliefs more efficient [23]. The potential pitfalls of using analogies include oversimplification which hinders more nuanced understanding necessary for understanding complex scenarios; a classical example is comparing an atom to a solar system misrepresents the probabilistic nature of electron orbits [24]. Analogies can also be misleading, leading to misconceptions or reinforcing flawed models [25], cause individuals to misjudge their familiarity with deeper scientific principles, or fail to connect concepts between domains [26].

In this paper analogies are used to bridge potentially different perspectives on engineering design education. The 2015 survey of capstone courses [27] found a split between an emphasis on process vs. product, leaning towards process. In chemical engineering [28] a 2022 survey found smaller programs (in terms of student enrollment) were more project-focused. Similarly in chemical engineering over 2/3^{rds} of projects were theoretical while Howe's 2015 survey showed nearly 2/3^{rds} of projects across disciplines emphasized product development. Similarly, while agile methods are used in software design, these methods are not as appropriate for design projects with longer development times. Such differences illustrate how disciplinary and individual perspectives inform engineering design learning experiences, and thus what students are able to be and do. The fact that there are different philosophies and methods for design is no surprise and is in fact desirable.

Historically, design methods have adapted to technological advances and societal and industry needs. Shifts from craftsmanship to science-based design in the 19th century to systems thinking—which made design a more team-based activity—in the 20th century there have been significant trends in how design is taught. More recently human centered design and increased adoption of socio-technical perspectives brings in elements of sustainability, ethics, and global challenges. These shifts have put more emphasis on teamwork, communication skills, and collaboration; the so-called transferable or professional skills. The range of methodologies—design thinking methods such as IDEO, use of simulation tools, system engineering for larger-scale projects, lifecycle assessments that emphasize environmental aspects, agile methods to promote iterative prototyping and adaptability—enables design to be adapted to many types of problems. While such breadth is a benefit in applying design methods *to* a range of issues and makes for interesting comparative studies *of* design [29], when it comes to teaching design in over-crowded engineering curricula methodological richness can be a drawback. Students realistically gain practice in one or two methods.

Analogies, as discussed previously, are useful in cross-domain understanding, and thus may help understand student learning in engineering design education. Here navigational analogies are used so it is worth defining what is meant and implied by this analogy. Navigation is a broad sense is a deliberate act of orienting oneself within a complex system of space, time, and context to reach a defined or evolving destination while continuously adapting to dynamic environmental, cognitive, and moral variables. Navigation incorporates elements of perception, decision-making, and purposeful action and implicitly or explicitly involves values. Navigators must decide not only the "how" but also the "why" of their journey while making ethical choices about their path, mode of travel, and what to prioritize during the journey. More specifically, navigation in the engineering design education refers to student action in the space set up within a course.

The two navigational analogies—map-based navigation and dead-reckoning—align to some extent with various aspects of design methods and practices. Navigation reflects a particular view of education: that students are agentic and able to make some choices, and that courses and the curriculum and/or the student themselves have some desired destination or outcome. The journey metaphor applies less to pipeline and more to pathway [30], [31] views of engineering education. Here education is a journey, aided by 'navigational skills', which can be thought of as relating to executive function and metacognition.

Map-based navigation [32] is most familiar to readers through their experience with powerful navigation tools such as Global Positioning Systems (GPS) and mapping software. In this analogy the destination is known and the goal is to plot the most efficient course. The more that is known about conditions along the intended route, the safer and more efficient the journey will likely be. Key heuristics for map-based navigation are to:

1. plot a route to the destination precisely,
2. stick to the route,
3. plot your current position with high accuracy, and
4. travel in a stable vessel.

These heuristics keep the navigator from drifting from the predetermined course. Today's level of access to information means that despite the hassles inherent to travel, few family trips end up like the Donner party [33]. This is a very familiar analogy. We adopt these heuristics almost unthinkingly since our vehicles and vessels are designed around this model of navigation. The analogies with design are obvious: have well-defined specifications, use project management tools to guide efforts and understand progress, and utilize teamwork and communication to ensure stability so that all members of the project can move the work forward. Note that such fixed maps and Cartesian grids are external to the navigator. Here, map-based navigation provides one end of a spectrum of thought processes used in design.

Before the availability of technology-based navigational tools, however, humans had to rely on a much more limited set of information, traveling long distances using a method known as dead-reckoning. This method of navigation relies on a different set of heuristics and mental models:

1. know your starting direction,
2. hold a steady course and estimate the distance traveled,
3. know when you get near your destination,
4. view yourself as stationary with the world moving around you (steer by the shape of the sky), and
5. design vessels for instability.

These skills are not readily accessible; accounts of dead-reckoning cultures show navigators spent a lifetime acquiring expertise in applying these heuristics [32], gaining social status through their expertise. Knowing direction and distance are self-explanatory but without instruments these required intimate knowledge of stars, ocean life and water color, and other contextual clues. Such clues let one adjust course as navigators got near to their destination. For example, subtle shifts in the sky's color at dawn or dusk due to atmospheric scattering help detect directions or land proximity and small differentiations between species determine proximity to different land masses. Taking the perspective that one is stationary and the world moves around you simplifies spatial reasoning in a dynamic environment. As quoted in [34], "Navigators using dead reckoning continuously engage in a process of orienting their bodies within the landscape, transforming movement itself into a form of knowing." Stars rise, move across the sky, and set as if they are flowing past the stationary observer. The sky is visualized as a "dome" that rotates around the navigator, and the dome's orientation relative to the horizon helps establish the path since constellations and specific stars rise and set at predictable points on the horizon. Similarly imagining oneself as stationary turns ocean swells into consistent wave trains beneath the canoe, with islands as moving markers that pass under specific stars or swell patterns. The canoe stays aligned relative to these swells and markers. These heuristics serve several purposes: 1) they eliminate the need for complex relative motion calculations, 2) they allow the navigator to integrate sensory data (stars, swells, wind) into a cohesive whole, and 3) they help the navigator maintain a constant orientation as conditions change. To ensure that continuous small adjustments to course get made, traditional watercraft are designed to be unstable, requiring the navigator's constant attention [32] so they are unable to take their mind away from the contextual clues while navigating. In short dead reckoning relies on skills of continuous awareness that dynamically updates a mental map on a regular basis.

While both map-based and dead-reckoning approaches seek to safely attain a destination, the skills and mindset required to do so have considerable differences. These differences show up in the level of reliance on either one's own expertise or external tools, the extent of 'embeddedness' in the journey itself, connection to and awareness of context and the external environment, how embodied the trip is, and whether one views of the space traveled through as either a dynamic, interconnected system or static scenery. The exploration done in this paper is not to make a claim that one form of navigational analogy is inherently better for building understanding of how students learn design, but rather to provide a way to contrast different curricular and pedagogical choices. For example, one could argue that skills learning in dead-reckoning align more with divergent phases of design while map-based skills align better with convergent phases [5].

Context and Study

This study was done at a Private, mid-Atlantic, Liberal Arts CollegE (PALACE). PALACE is a medium-sized, elite, primarily-white liberal arts institution that is located in a rural area in the mid-Atlantic region comprised of three colleges including arts & sciences, engineering, and management. The College of Engineering has six departments of which electrical and computer engineering (ECE) is one. Enrollment is typically about 100 students in all four years of both degree programs. There is a required four-year design sequence that is common to both degree programs. In the first year students take two design courses, one focused on engineering broadly and the other on design in ECE. In the second year a half credit design course focuses on fabrication and test and measurement. In the third year a half credit course focus on problem identification and understanding context and value. The senior year has a two-credit, year-long capstone experience. The full sequence of six courses is five credits (20 credit hours). A key focus of the design courses is to help students develop autonomy [35], [36], [37], [38] since that has been shown to positively impact academic performance. While the courses early in the program provide structure and support, these are gradually relaxed over the four years until in the capstone course students are operating mostly independently. While the first design course is not taught by the department, the five remaining courses use a common framework for design, shown in Figure 1. This framework is composed of eight overlapping perspectives, each of which are used throughout the design process; this is not a linear, sequential design cycle [39]. Different courses focus more in-depth on some of the perspectives.

Briefly, Figure 1 captures eight different ways to view a design project that serve as lenses to view a project. The hypothesis, backed by research on design methods [39], [40], is that as students gain expertise in design they are able to more rapidly shift between these eight perspectives rather than seeing design as a linear or fixed cyclical process. Figure 1 summarizes the eight perspectives students are taught. For each perspective students communicate their product and process through formal representations, the outer octagon. In the courses discussed subsequently it is hypothesized that representations support results, and results indicate increasing design ability in each of the eight domains. This structure is used both to organize courses and explain design processes to students.

Design courses in the second through fourth years emphasize representations as an integral element of the design process. Here the term 'representation' refers to diagrams or models that portray some aspect of the design process. Representational skills have been tied to design creativity [41] and process [42]. Representations are also important in education in both math and chemistry [43] and have been shown to relate to how well engineering students can create models [44]. Students include multiple representations in the artifacts they create in the course.

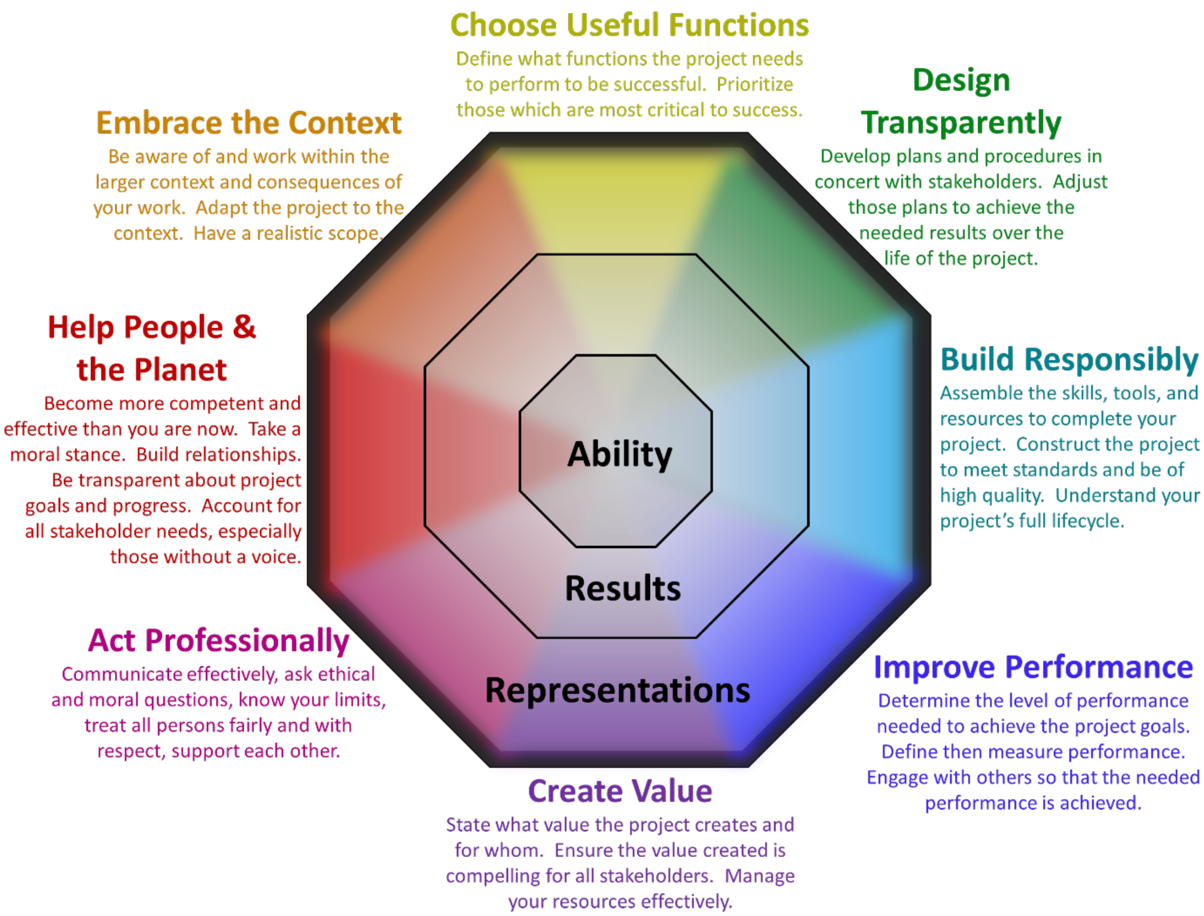

Figure 1: Eight design perspectives supported in the six-course design sequence in the ECE curriculum at PALACE.

This paper focuses on the final three courses: half-credit courses in the second and third years of the program and the year-long capstone course in the final year. The organization and structure of these courses has previously been reported [45]. In the second-year course students individually construct an internet of things (IoT) appliance that integrates sensing, display, and cloud storage and processing [46]. The course is highly scaffolded, walking students through the steps of constructing an IOT device in a sequential fashion; the devices the students create are functionally identical except for their appearance, the sensors used, and how they are programmed to perform various functions. If students make a mistake in constructing their IoT project considerable help is available to ensure they have a functioning platform by the end of the course. The goal of the second-year course is to teach students skills in 'Design Transparently', 'Build Responsibly', and 'Improve Performance' from Figure 1.

The third-year course, in contrast, has the class choose one of the United Nations Sustainable Development Goals (UNSDGs) and understand the context, history, and background of the issue before designing a technical solution to some aspect of the goal on a small (3-4 person) team [47]. This course emphasizes problem identification and understanding context. Representations developed in the course focus on 'Help People & the Planet', 'Embrace the Context', 'Choose Useful Functions', and 'Create Value' elements of Figure 1. By the end of the semester student teams utilize skills gained in the second-year course to create a working minimum viable product (MVP) that addresses some aspect of the UNSDG for a particular group. Student teams are given a large amount of autonomy in project selection, with regular check-ins and feedback.

In the year-long capstone course sequence students take on projects for external clients – companies, non-profits, or campus organizations. The capstone course is integrative, that is students synthesize prior experiences from the second- and third-year courses in developing a prototype solution for their client. Students are in larger teams—six to seven students—and on each team two students take on complementary project management roles. The teams self-define schedules and regular check-ins provide feedback on their progress. The course is organized roughly on a test-vee [48] model but incorporates many ideas from the lean start-up community [49].

From the perspective of the student, the second- and third-year courses provide intentionally contrasting experiences of design, with the second-year course towards the map-based navigation analogy end of the spectrum, and the third-year course more aligned with the dead-reckoning analogy end. This contrast is not accidental, the faculty in the ECE Department at PALACE intentionally designed these courses to give students a range of design experiences under the assumption they would become better design engineers by having contrasting experiences. The range of experiences also aligns with PALACE's mission as a liberal arts institution; exposure to a range of perspectives is central to historical conceptions of liberal education [50]. The capstone course sequence, in contrast, can be thought of as apprentice navigator's first voyage. While students are not explicitly taught these analogies, their team is able to self-organize how they approach the design, and so these analogies serve as lenses to examine student actions.

The rest of the paper analyzes how these two analogies, which guided the development of the second- and third-year courses play out in terms of student experience. To gain insights into student experience we look at a limited set of artifacts created in the courses. For the second-year course these are end-of-semester reports in a data sheet format that were compiled from weekly 'design assignments' corresponding to each separate step in the IoT platform. Students received written feedback and scores on each of the design assignments. End-of-semester electronic portfolios [51] were also examined. E-portfolios were based on a template that had students identify a project they would like to build, explain how it related to their learning in the class, then answer several reflective prompts. For the third-year course the first artifacts are team design reports compiled in three phases over the semester. Students received feedback after each phase. The second artifacts are weekly, unprompted reflections by individual students that course instructors responded to. Students also created e-portfolios based on a Hero's Journey prompt [52]. For the capstone course the artifacts from the first half of the course are weekly reflections and team end-of-semester reports. The reports received feedback student teams could respond to, and instructors engaged in textual dialog with students on the weekly reflections. For all three courses artifacts from the Fall 2024 semester were analyzed; additional artifacts and data for several years is available; a more in-depth analysis will be presented in a journal publication. No longitudinal connections are made in this work.

To understand how well the two navigational analogies capture student experiences across the three courses the artifacts were qualitatively evaluated based upon student self-reports of using the heuristics listed previously for each analogy. Heuristics are mental shortcuts or rules of thumb students in design courses use to make decisions or solve problems efficiently, often under conditions of uncertainty or limited information. Heuristics sometimes lead to biases or errors, but help to simplify complex tasks by providing actionable guidelines and helping students make quick, adaptive decisions. In engineering Billy Vaughn Koen defined heuristics as "anything that provides a plausible aid or direction in the solution of a problem but is in the final analysis unjustified, incapable of justification, and potentially fallible" [53].

The hypothesis of this work is that the analogies of map-based and dead-reckoning navigation can contrast student experiences in design courses in a way that enables wide-ranging discussions of design. Student design experiences that align with the heuristics inherent to map-based navigation include: having a defined product; regular use of or adherence to specifications; having or developing a plan for the design project; adhering to the plan that is developed to minimize deviation from specifications; viewing progress as fractional achievement of a goal; monitoring deviation from the plan and making efforts to self-correct; determining progress relative to the plan to ensure the project is finished on time and within budget; and creating as stable a project environment as possible. Since humans often take stability for granted, this last element could be indicated by lack of references to instabilities, chaos, or unexpected issues. In contrast experiences aligned with the dead-reckoning analogy could include: holistic and high-level rather than specific and technical goals; development of specifications late in the project; engaging in problem identification; reiterating or revisiting project goals regularly; evaluating progress based on impact or value rather than achieving specifications; creating milestones or indicators of progress after the project goals become more clear; seeing the effort as focused on the team and one's own learning rather than externally-mandated deliverables; holistic rather than detail-oriented project management; and being willing to change the design or project scope, shift roles, pivot, or shift directions to adapt in real time. In other words, a recognition that fluidness in roles and tasks can lead to better outcomes.

In drawing parallels between student experiences reported in the artifacts and the navigational analogies, best practices for comparative studies were followed. The scope of the analogy was limited to student experiences in these courses, and comparisons are grounded in student experience. The analogies are refined, as described subsequently [54]. The analogies serve as "boundary objects" [55] that help faculty across the ECE Department discuss different curricular approaches [56] to engineering design. Since design is highly nuanced, oversimplification was avoided by recognizing the limits and potential false equivalencies [57] of navigational analogies as discussed later.

Results

The artifacts described in the previous section were evaluated for references to student experiences in completing and managing projects in the second-year, third-year, and capstone design classes. The student artifacts are self-reports; the projects themselves were not evaluated for this paper. While self-reports can be prone to errors [58], it is hypothesized self-reports on student strategies and the heuristics they applied will reflect the student's lived experience and thus provide insights into the heuristics they used. All the artifacts were turned into PDF files then uploaded to Google NotebookLM. Queries were iteratively tested to pull out descriptions of student actions and each description was read and coded. Following this scanning process sections of the original artifacts were then read in depth.

Second-year course: The second-year course provides a highly structured introduction to electronic design, fabrication, and testing with weekly milestones. Structurally it is purposely organized using the map-based analogy. This was reflected in the project datasheets - students provided details of destination (project outcomes) but not of the journey (reflections on process). That is, they focused almost exclusively on reporting measured specifications showing that the project goals (destination) were achieved with high fidelity. The assignment structure promoted thinking in the map-based mode, focusing on knowing defined steps and quantization of progress in detail. Students had common experiences around fixed and well-defined milestones, and developed proficiency in specific skills related to project milestones. Despite the structure, however, not every student's journey was the same. Most variations occurred in the later phase of the project. Issues like sensor calibration, fine-tuning, and side explorations came when students were asked to customize their device, i.e. deviate off the planned course, at the end of the project.

Student reflections showed that despite the highly structured nature of the course the experiences of the journey varied, and are connected to how confident students were in their abilities. The focus on hands-on learning was seen by students as important in their development. Despite the organized structure of the course, using a hands-on approach provided a needed 'messiness': "*Failing certain things is the only way you learn, and I ran into this many times through the class design assignments*" or "*[this class] gave me a better sense of how messy and iterative the design process is in real life*". Students noted that the "maps" (i.e. design representations) they were given (e.g. block diagrams and focusing on sub-systems) provided needed guidance to breaking down the project into manageable components. One area that students struggled more with was making 'course corrections' through testing. This emerged as a recurring theme, with many students acknowledging its importance while also revealing varying levels of comfort with the process. Overall, the structured, i.e. map-based, approach to course design increased awareness of the interconnectedness of system components, the advantages of a more structured approach to project planning, and the importance of breaking down complex tasks into manageable sub-systems.

In terms of the dead-reckoning analogy, student reflections primarily focus on technical aspects of the design process, such as fabrication, testing, and understanding subsystems and did not discuss more fluid, adaptive aspects of project management aligned with the dead-reckoning analogy. While some reflections do reveal instances where students did not have detailed instructions or had to grapple with ambiguity, the reflections don't elaborate on how they addressed these challenges or adapted their approach. In other words the course design framework directly translated to how students practiced design.

Third-year course: The third-year course was designed around the dead-reckoning analogy by giving students flexible tools that enabled them to chart their own course. Rather than specifying an end goal, student teams developed the goal themselves and were encouraged to pivot in direction at need. The lack of specific technical requirements provided a 'navigational challenge', engaging students in problem identification and scope refinement. One student, while grappling with the enormity of the Zero Hunger (UNSDG) goal, questioned, "*Should we focus simply on ways to grow more crops to help struggling communities? or should we somehow develop a solution that relates to fixing social structures?*" Such internal debates were common in student reflections, underscoring student efforts to reconcile a grand societal challenge with the practical limitations of their engineering skillset. To resolve these tensions a set of design representations (diagrams) introduced throughout the course provided heuristics (rather than specific directions) for navigation. Asking student teams to develop structured representations such as system maps and flow and block diagrams helped teams dynamically navigate by breaking down the complex, ill-defined problem (journey) into manageable components (clues) and plan next steps systematically. One student indicated this helped map the journey: "*Seeing how an entire web of (seemingly unrelated) concepts connect together to form a cohesive story about a system is fascinating, and it certainly allows us to have a much better understanding about the problem we are addressing*" suggesting that the representations served as tools for thinking and understanding the problem space. It is important to highlight the creation and modification of representations served as just-in-time course corrections rather than structured long-term planning.

The less-structured approach supported a shift towards student ownership as the project progressed, "*This is where we need to shift from simply learning systems to owning them and applying them to our project.*" The open-ended nature of the project presented challenges for some students who felt "*lost in the course*" with "*everything seems very unclear and vague*" as might be expected for a novice navigator. This lack of certainty did, however, result in adaptability in the design process. One team's sensor proved unreliable, forcing them to pivot and eliciting this reflection: "*Reflecting on this week, we see how adapting to setbacks can open up opportunities for other innovative ideas...The shift from a single unreliable sensor to a more robust hybrid model will strengthen our project in the end*". The student reflections reveal a learning experience characterized by a balance between structured guidance and self-directed exploration by being provided with tools and frameworks (navigational aids) to approach the complex design challenge. Without specified outcomes teams were responsible for owning the process, adapting to setbacks, and creating a solution that delivered value to the end user.

The idea of instability and course corrections emerged strongly in this data set. The teams initial ideas were often challenged through required interviews, feedback from instructors, and teams' own research. The more dead-reckoning approach fostered adaptability and a willingness to pivot when necessary. There is little evidence, however, for team instability or role-shifting within teams. However, the need to adapt and take ownership of the project implicitly required a degree of flexibility in how tasks were distributed and managed. In terms of iterating to a destination as the project progressed, teams developed more concrete milestones and indicators of progress over time. The various design representations served as more tangible markers of their advancement. While not tightly specified, the representations were used as 'navigational aids' that helped teams stay organized, track their progress, and maintain momentum. In dead reckoning this corresponds to "steering by the shape of the sky" in that such representations were gave direction during the voyage rather than serving as a pre-specified destination. Students also had a tendency to abandon representations when they ceased to provide immediately useful navigational information despite the instructors' admonishments to keep all representations current.

Overall, the results of using the dead-reckoning analogy in designing course structure resulted in students who reported developing a system-level understanding of the problem space, being competent with creating navigational aids (representations), iteratively refining their project to adapt to unforeseen challenges, and successfully concluding creating an MVP (arriving at an acceptable destination). Students did, however, struggle with the open-ended nature of the project and the ambiguity surrounding expectations. Although these concerns abated with time, students reported this as a significant stressor early in the semester. The shift from the well-structured map-based approach to the more open-ended dead-reckoning model was further complicated by the focus on user value, and students reported they had difficulties anticipating the needs and perspectives of the end user.

Capstone Design: The capstone course is focused on meeting the needs of internal or external clients. Teams of five to seven students are assigned a year-long project and given considerable autonomy in how to address it. While they are required to explain their approach using representations both new and learned in the prior year, how they apply them and which representations they use are not fixed. In the analogy of navigation, the capstone course might be considered students' first independent voyage as novice navigators (designers). In this spirit the instructors provide feedback but avoided any direct guidance for the project.

Student teams used both map-based and dead-reckoning approaches to design in their capstone projects. Based on end-of-semester reports, map-based approaches were supported by regular design check-ins and the use of design representations to specify a goal. In essence having a defined destination and a map to get there provides a sense of comfort and security. Based on their prior experiences in design courses students were able to retrospectively discuss how they used representations to define and independently move towards a project conclusion. However, the dead-reckoning analogy is more prominent in real-time reflections, revealing an underlying process of adaptation and emergent decision-making. Teams frequently revisited and redefined their project goals based on new information from client meetings, interviews, and research. For example, one team had their initial assumptions about the project scope were challenged by the client's existing Minimum Viable Product (MVP): "*It certainly changed our design plans... It means that the divergent phase of our design process has to keep in mind the plans of the client and how the MVP is designed to operate in its current ideation*" illustrating a shift from a predefined path to a more dynamic approach based on emerging information.

Based partly on how the course was structured, all teams put strong emphasis on value creation and impact over strict adherence to specifications: "*Fundamentally, there is no issue with our project never developing a clear direction. Our job as engineers is to serve, provide value to the client — how that is done does not follow a formula but can rather come in many different forms, on many different timelines.*" The willingness to adapt and pivot is also evident in teams' experiences with changing roles and responsibilities. Students reported regularly shifting their priorities – for example from research to project management. Other students reported being initially unsure of their roles but gradually defining them over time based on team needs. Students' reflections reveal a tension between the two analogies. While the requirements of grading and scheduling required they create some framework for the course (a map), this was often seen in tension with the real-world complexities of their projects which demanded flexibility and adaptation. A student observed, "*One thing that I'm pretty unfamiliar with is kind of adjusting to a more realistic approach to engineering than what I think we've had in courses in the past*", highlighting a dawning recognition that design processes are not linear and require navigating ambiguity and evolving requirements.

The reflections and reports also shed light on how students viewed their role in navigating design – either as being steered to a defined destination or having control and ownership of the project outcome. Student positionality was nuanced, with evidence suggesting a tension between a transactional, grade-oriented perspective and a professional, ownership-driven approach. While the structured course framework and emphasis on deliverables encouraged a transactional mindset at times, student reflections also showed a shift towards a deeper sense of project ownership and professional responsibility. Students viewed mandatory research requirements as "assignments", and the reflections suggest this contributed to a mindset of completing tasks primarily for grades rather than as supporting the project. In terms of project ownership, reflections emphasize the importance of delivering value to the client and understanding their needs. Students also actively took ownership of tasks, going beyond assigned roles. Teams and individuals readily adapted to changing project requirements and client feedback as well as showing a willingness to shift roles. The fact that lack of clear goals led to a less stable environment was reported in reflections by the significance student places on communication, collaboration, and problem-solving, recognizing these skills as essential for professional success. The shift to the dead-reckoning analogy did depend to some degree on students' prior experience. Students with prior experience in design courses or industry internships seemed more comfortable embracing ownership and navigating ambiguity. Additionally, there were significant individual differences – some students demonstrated a stronger intrinsic drive to deliver a valuable product by honing in iteratively (dead reckoning), while others primarily focused on fulfilling course requirements illustrating a more map-based mentality.

Discussion and Conclusion

In this paper the author introduces two navigational analogies for teaching engineering design. The map-based analogy frames the journey through a design project as being to a well-specified destination and guided by metrics and plans. In this analogy accuracy and instrumentation are key to making the voyage safely. The second analogy is that of dead-reckoning, where arriving safely is just as important, but rather than following a set course the voyager sets out in a known direction but the path is constantly iterated upon. They must actively pay attention to their surroundings, making constant and iterative course changes based on emerging information. Focusing on the present location and environment rather than the destination, this analogy captures a more self-contained view where integrity of the project is prioritized over reaching a defined end point. These analogies indirectly and imperfectly capture many elements of design including: reducing risk either through deep expertise or procedural certainty, the tensions between divergence and convergence, long-standing tensions between craftsmanship and mass-production [59], and questions of who 'owns' a design, the designer or the client. These analogies are used as two poles on a spectrum to conceptualize teaching design.

The two analogies were used as lenses to view artifacts of student learning across a three-course design sequence stretching over three years. The courses reflect different course goals and intentions of faculty who designed the design courses. The order and structure of the courses also reflects a set of faculty beliefs about learning. The beliefs are that autonomy and agency—i.e. student choice—are central to engineering design education, but these are learned skills, and developing them needs to be carefully scaffolded. In essence this in an aspect of the old debate in the social science about structure vs. agency and there are parallels between the two navigational analogies and structure and agency. Structure, in this context, refers elements reflecting one set of faculty beliefs that include: deadlines, deliverables, grading policies and rubrics, and assumed and assigned roles as well as norms. These elements establish a framework and set expectations for student behavior, encouraging a transactional approach focused on fulfilling requirements to demonstrate progress in learning. Agency, on the other hand, refers to the students' capacity to make choices, take initiative, and shape their learning experience. In other words, navigate.

A clear progression emerges in the interplay of structure and agency as expressed in student artifacts across the three years. The second-year course's focus on fundamental skills and defined assignments is achieved through structure that limits student agency. This structure, however, lays a foundation for future agency by equipping students with the essential technical skills and knowledge needed for more open-ended design challenges. By introducing concepts like system mapping and client interaction in the third-year course, emphasis shifts to understanding problems and iteratively developing solutions. Ambiguity (uncertainty of destination) provides a scaffold for agency to develop, allowing students to make choices within a defined framework while tackling real-world constraints and ambiguities. In the capstone course the project takes center stage, with client needs and real-world constraints driving decision-making. Students have significant agency in shaping project direction, defining roles, and managing timelines. The reflections and reports indicate that students demonstrate a high degree of ownership, proactively seeking information, adapting to changing circumstances, and reflecting on their growth as professionals.

Structure and agency are thus mutually supporting. Like maps in navigation, structure provides a foundation of knowledge and skills, introduces frameworks and processes for problem-solving, and supports low-stakes decision-making within a 'safe' context. Ideally as students gain experience and confidence, the structure allows for greater autonomy while still providing essential guidance and accountability. Structure and agency can, however, clash; student artifacts express frustration with restrictive deadlines or a lack of clarity in expectations. Overall, the data reveals a deliberate shift towards increasing agency throughout the three years, with structure serving as a scaffold that gradually recedes as students develop the confidence and skills to take ownership of their learning and professional development. In other words, students are becoming better at navigating.

In summary, navigational analogies are explored here as lenses into thinking about engineering design courses. The analogies reflect different belief systems but, as discussed earlier, analogies are never perfectly faithful representations. They can encourage understanding, bridge gaps between domains or perspectives, and provide alternative and accessible points of view. In this paper navigational analogies were chosen due to the author's interest and view of design as a journey; others may find other analogies are more appropriate. It is worth noting that there are no implied value judgements between the two analogies. Design as an activity is highly contingent, focusing on what is appropriate [29]; for design at PALACE using the map-based analogy to inform design earlier in the curriculum and shifting consciously to the dead-reckoning frame later made sense. Other programs may have different priorities. However, the analogies *do* have historical and cultural aspects; these are intentional. The map-based analogy represents a techo-centric approach that reflects modern values and faith in technology. In other words, it is an ideal of how engineering developed from the 19th to the 21st century to scale and mechanize production. The dead-reckoning approach, in contrast, relies on deep human expertise and connection to the environment. It recognizes uncertainty and impermanence, taking a careful and iterative approach. As authors have highlighted, dead-reckoning is an embodied knowledge: "Navigators using dead reckoning continuously engage in a process of orienting their bodies within the landscape, transforming movement itself into a form of knowing." [34]

Technology is ultimately about convenience. What effort can I save? The work technology displaces is human work, often backbreaking or degrading, but sometimes sublime. As the next generation of subsumes the technologies of today the work, no longer valued, fades from memory and becomes quaint (as the meaning of the word 'quaint' itself has changed). This is as true in education as it is in engineering and navigation. From this perspective map-based navigation or constraint-driven design seem to be the best way to prepare students. But this perspective arises from the fact that society increasingly frames education as a means to economic ends—in a utilitarian way—so we forget that education is also the way an individual learns their own path through life. And all our paths are different and need skills to navigate. Within engineering there has always been a tension between "learning the basics" and "being creative" that is difficult to resolve; the map-based analogy better aligns with engineers' epistemology. But our beliefs about education matter; education and educational systems serve critical purposes in society. Education is structured for certain outcomes, yet structure determines outcomes in a way that is often invisible to those who exist within the structures. The structures we currently exist in were established in an age where a transition from an agricultural to an industrial society was underway. It is clear we are now transitioning from a manufacturing to some other form of society, and in this transition engineering education will also need to change. The path for that journey is not well-marked for we have not yet taken it. So perhaps the skills of dead-reckoning are still needed.

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