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Development of a Diagnose-and-Solve Problem for an Aerospace Engineering Classroom: A Design Case in Operationalizing Jonassen's Design Theory of Problem Solving

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Abstract

Motivated by challenges faced by faculty to develop "good" problems for engineering classrooms, we report on the development and implementation of a diagnose-and-solve problem for an introductory aerospace engineering course. Our reporting follows the structure of a design case, a genre of scholarly and empirical reporting of the process and product behind the design of a learning experience. The objective is to demonstrate our efforts to operationalize Jonassen's design theory of problem solving—inclusive of problem typology and characteristics of structuredness and complexity—as a framework to govern problem design and facilitation decisions. We describe the integration of field data from a middle school rocket launch outreach event into a problem-based learning experience for undergraduate aerospace engineers. Using hierarchical task analysis as a pedagogical reflection aid, we discuss important assumptions related to student engagement with the problem from the perspective of the problem designer and facilitator. Reflections on successes and challenges are shared.

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Introduction

The core competency of an engineer is problem solving (Passow & Passow, 2017), yet it has long been recognized that the types of problems engineering undergraduates face in classrooms are not well-suited to preparing them for practice (Jonassen, 2014). Even as curricula have moved toward pedagogical practices like problem- and project-based learning (P/PjBL) to overcome this misalignment, there remain critical challenges to their effective adoption (Chen et al., 2021; Olewnik et al., 2023). This paper contends with one such challenge, namely, the design and implementation of "good" engineering problems. Colloquially, a good engineering problem is one that is authentic (i.e., requires students to work within a real-world context) and representative of the types of problems engineers might expect to see in practice (Jonassen, 2014; Jonassen et al., 2006). The problems imagined for contemporary engineering education environments should move beyond the well-structured and abstracted math problems focused on just solving tasks (Bucciarelli, 1994; Jonassen et al., 2006), to ones that require the defining and framing of problems (Downey, 2005; Svihla et al., 2023), exercising judgement (Francis et al., 2022; Price et al., 2022; Swenson et al., 2019), and constructing models in the service of understanding and improving a system (Carberry & McKenna, 2014).

This paper reports on efforts to design and implement "good" problems within an introductory course in aerospace engineering at an R1 institution in the Southeastern United States. Following a PBL approach (Felder et al., 2011; Hmelo-Silver et al., 2019; Kolmos & de Graaff, 2014), students worked in small groups to engage in multiple ill-structured, complex, and authentic aerospace engineering problems with guidance from a facilitator. Over two years, as part of a design-based research project, we designed and implemented four different types of problems common to engineering (Jonassen, 2014): case analysis, selection (decision-making), design, and diagnose-and-solve. We focus reporting on the development and implementation of the diagnose-and-solve (DS) problem as a specific design case. We report on this problem for two reasons. First, it was the last problem to be designed and implemented during the two years of the project and therefore, it was the most informed of the four problems that were developed. Second, intentional design of a diagnose-and-solve problem for problem-based learning, as opposed to an emergent one that you might expect in a project-based design course, is rare based on our personal experiences teaching in engineering institutions and our knowledge of relevant literature. In this regard, it is an opportunity to share a unique experience.

We are motivated by prior work related to this project (Olewnik et al., 2023) in which we have concluded that reporting on the critical challenges of PBL, and efforts to overcome those challenges, are often insufficiently granular for other practitioners. Our reporting follows the convention of a design case (Svihla et al., 2023), a genre of scholarly and empirical reporting about the process behind the design of a learning experience and relevant details about the resulting product. We present our experience and insights grounded in a theoretical framework that might make those insights tractable and actionable for others within and beyond the aerospace engineering education context of our work.

Two objectives frame our presentation. First, we show how Jonassen's design theory of problem solving (Jonassen, 2000) provided a guiding framework for design within the pedagogical framework of backward design

(Wiggins & McTighe, 2005). Second, we show how concept mapping and learning hierarchy analysis (Jonassen et al., 1999) supported a pedagogical reflection process that made relevant knowledge and problem characteristics of ill-structuredness and complexity of the problem salient, both of which informed facilitation strategies. In serving these objectives, a contribution of this paper is the presentation of an emergent design process for problem-based learning in engineering contexts.

Problem design was a collaborative effort among the authors of this paper. We are co-principal investigators on the grant that has informed this work and we both have expertise and research experience related to design theory and methodology. Our general interest and experience with the process and discourse of design has been an important influence on our approach and thinking about this work. The first author (Dr. F, he/him) is a faculty member in mechanical and aerospace engineering whose research focuses on systems architecting and decision-making. He also is the instructor of the course where this problem was implemented. The second author (Dr. O, he/him) is a faculty member in engineering education whose research is focused on development and support of curricular and co-curricular learning environments, particularly as it relates to ensuring that learning in both contexts is better aligned with professional practice. This work is an extension of their prior research to operationalize Jonassen's conceptual framework of problem typology as a discourse scaffold and metacognitive aid to support student engagement with ill-defined problems (Olewnik et al., 2026). The research team has also included multiple graduate students from engineering and education whose involvement has been vital to problem creation and to a community of discourse that has helped to make ideas shared through this manuscript more salient. One of those students, L, was instrumental in the creation of the diagnose-and-solve problem detailed in this work. They provided calculations and estimates from pictures and videos that were used from a problem facilitation perspective to help resolve aspects of the problem's ill-structuredness.

Context

This problem was created for a second-year Introduction to Aerospace Engineering course at an R1 institution in the southeastern United States. This course, offered in the fall of the sophomore year, is situated as one of the first aerospace engineering-specific courses, as engineering students at this institution have a common first-year curriculum. A typical student will also be enrolled in a third calculus course, a second physics course and its associated lab, engineering statics, and a specialized aerospace course that covers aircraft performance analysis and orbital mechanics. Lab and lecture courses built around well-defined, single solution problems dominate the curriculum. While students may engage with projects in each course, the primary mode of assessment is homework and exams. These problems are fully defined, in that all needed information is provided, and there is one accepted answer to each problem. In their senior year, students complete a two-semester capstone design course where they choose between a rocketry, aircraft, or space option. However, there are limited opportunities within the rest of the curriculum for students to engage with ill-structured and open problems.

The Introduction to Aerospace Engineering course was added to the curriculum in 2014 so that students could gain a broader perspective of aerospace engineering. It is a 1-credit-hour course and meets once per week for 75 minutes. Initial course construction was structured around faculty-delivered lectures on different aerospace topics, and students completed homework and small-group projects. In 2022, the authors began a redesign of this course using a PBL pedagogy based on Jonassen's design theory of problem solving (Jonassen, 2000, 2010). Weekly, faculty-delivered, lectures were replaced by student groups engaging with a series of ill-structured, complex, and authentic aerospace engineering problems. The focus of this redesign was exposing students to ill-defined, open problem solving.

This introductory course was positioned as the first effort in a curriculum redesign where students would have greater agency in defining and solving problems. Over the 15-week semester, students engage with three problem types common to engineering: case analysis, selection (decision-making), and diagnose-and-solve (see Figure 1). Students engage with each problem type over a 3–5-week period. Each problem used either a NASA student launch competition or AIAA design-build-fly context.

Figure 1. The Course is Built Around Engagement with Three Different Types of Problems Over 15 Weeks

Given the new format of this course, the faculty's role transitioned from lecturer to one of problem designer, facilitator, and assessor. There was no lecture (i.e., no derivation of theory and faculty modeling of problem solving that students would mimic later). Student engagement included both a single-week framing exercise and a multi-week problem engagement opportunity. Single-week framing exercises were instructor-led and focused on introducing students to the problem type and driving classroom discussion around the process that might be followed for successful problem engagement. The objective of the framing exercise was for students to focus on thinking through the problem engagement process and relevant tasks rather than arriving at a solution. This framing exercise served as a hard scaffold applicable to the multi-week problem where students engage the problem with greater autonomy. Multi-week problems were student-led. The faculty would interact with individual groups during the class session to guide their problem engagement and answer questions. For all multi-week problems, students submitted weekly slide decks documenting their progress. Their final submission was a comprehensive slide deck that documented their work and justifications supporting their final answer.

Theoretical Framework: An Emergent PBL Design Process

The design process (see Figure 2) that governed the development of this problem, and others used in the course, comprises elements from four theoretical frameworks brought together as part of exploratory design-based research on supporting problem-based learning environments. Those frameworks include backward design (Wiggins & McTighe, 2005), a design theory of problem solving (Jonassen, 2000, 2010), concept mapping (Novak & Cañas, 2006), and learning hierarchy analysis (Jonassen et al., 1999). The incorporation of these four elements is toward developing a reflective approach to pedagogical design of problem-solving experiences for engineering students that are better aligned with the ways of thinking and knowing found in practice, as compared to the well-structured problem sets that remain at the center of much undergraduate engineering education in the United States.

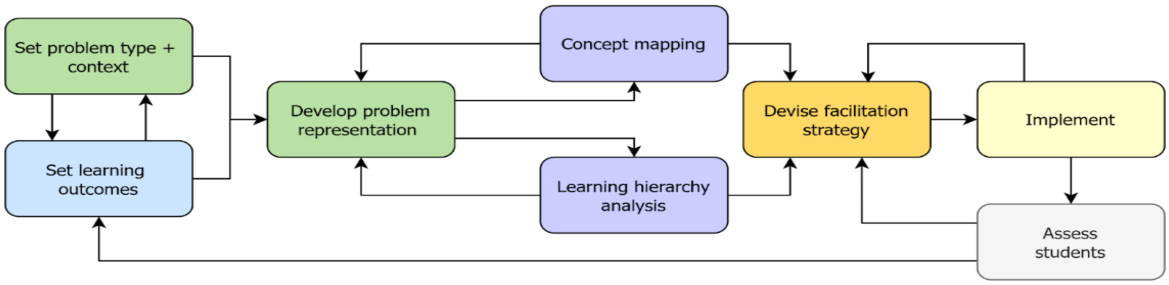

Figure 2. Emergent Design Process for Problem-Based Learning

Backward design is a set of guiding principles for the design of learning experiences that starts with consideration of learning outcomes and assessment (i.e., acceptable evidence of learning) and then shifts to development of experiences aligned with those considerations. This approach is important to avoiding the development of learning experiences that become more focused on covering content and performing activities than specific learning outcomes (Wiggins & McTighe, 2005). In undergraduate engineering education, a focus on coverage of technical content often results in learning activities that fail to accommodate important and professionally relevant forms of learning and professional preparedness (Jonassen et al., 2006; Lord & Chen, 2014; Passow & Passow, 2017). This overarching pedagogical design strategy is reflected in the design stage of "set learning outcomes" in Figure 2.

Complementing backward design is Jonassen's design theory of problem solving (Jonassen, 2000, 2010). Particular elements of the theory that were operationalized here include consideration of different problem types and problem characteristics of structuredness and complexity. Jonassen's presentation of problem typology is domain agnostic but provides benchmark definitions for each type of problem (Jonassen, 2000). Operationalizing the theory requires consideration of a particular domain (i.e., engineering) and the scenarios and practices found therein. This is reflected in the design stage of "set problem type and context" in Figure 2.

These initial stages of setting problem type and context, and setting learning outcomes, are concurrent stages that were in conversation with one another. Together, they effectively represent the requirement development phase common to design procedures (e.g., NASA, 2007; Ulrich & Eppinger, 2011), that lead into a concept development phase represented by the design stage of "develop problem representation" in Figure 2. The problem type is a fundamental determination that informs how the problem might be represented to students in terms of an initial prompt that leads to appropriate goal setting and tasks, relevant (and potentially irrelevant) information that motivates knowledge construction with appropriate facilitation, and students' familiarity with the domain (Olewnik et al., 2026). The problem presented in this paper is an instance of a diagnose-and-solve (DS) problem, which are common in technical contexts. DS problems require problem solvers to identify fault(s) within an existing system, and then to propose, evaluate and select solutions that bring the system into a state of proper function (Jonassen, 2000). In our view, DS problems bring together elements of the three most common problems faced by practicing engineers—troubleshooting, selection (decision-making), and design (Jonassen et al., 2006).

After an initial problem representation is developed, the next stage of design is one of pedagogical reflection (Mawer et al., 2024), enabled by concept mapping and learning hierarchy analysis. Concept maps are used to construct a hierarchical representation of knowledge, with specific concepts represented as nodes and connections between nodes describing the relationships among concepts (Jonassen & Marra, 1994; Novak & Cañas, 2006). Elements of a concept map include concepts, propositions that relate two or more concepts through linking words to form a statement, and (potentially) crosslinks that relate concepts that occur in different parts of the map. We used concept mapping as a structured approach to document problem representations and the key components of knowledge necessary to engage those problems (Mawer et al., 2024). Specifically, we consider knowledge types of conceptual, domain (experiential), structural, and procedural knowledge (Jonassen, 2000; Mawer et al., 2024), which we have defined previously (Mawer et al., 2024a).

Learning hierarchy analysis (LHA) supports the identification of prerequisite skills or knowledge and their ordering necessary to achieve the final learning outcome (Jonassen et al., 1999)—i.e., identification of the tasks necessary to reach a solution. We have used LHA as a structured approach to visualize and document the tasks that the facilitator envisions problem solvers engaging in order to reach a solution. LHA as a visualization approach is useful for two reasons. First, relative to the well-structured, end-of-chapter problems common in engineering classrooms, the problems implemented here do not lend themselves to a typical "solution manual." An LHA supports the creation of a more abstract presentation of solution relevant tasks, which could be shared with students later for comparison with their own approach.

Second, once constructed, the LHA allows the problem designer to consider problem characteristics of (ill-)structuredness and complexity by asking two questions: 1) Which LHA tasks are important to resolving problem ill-structuredness? and 2) Which LHA tasks are associated with resolving problem complexity? Ill-structured problems include problem elements that are uncertain or unknown, have multiple evaluation criteria and possible solutions, and require that problem solvers impart judgements or beliefs to arrive at one of multiple possible solutions (Jonassen, 2000). Complexity considers the number of problem elements, their interactions, and the functional relationships among elements (Jonassen, 2000). The stability of problem elements and their relationships is also a factor in problem complexity; if problem elements change, complexity increases.

As pedagogical reflection tools, concept mapping and LHA are intended to support evaluation and iterative updating of the problem representation, and the development of a facilitation strategy. There are three elements of facilitation planning including information/knowledge management, hard scaffolding, and soft scaffolding, all of which may overlap one another. Information/knowledge management considers how students will acquire relevant information/knowledge for the problem. For example, will information about environmental conditions relevant to the problem be specified in the representation, or will students be expected to find that information? If students are expected to find that information, will they be directed to potential resources, or expected to find resources for themselves? Similarly, if developing a model representative of a system's behavior is a potential task in the LHA, will students be provided relevant theory or expected to acquire that knowledge themselves? Consideration of hard scaffolding informs the delivery mode and level of abstraction used to facilitate students' problem engagement. For example, hard scaffolding could take form in facilitatory modeling the use of a particular theory through an example problem; this form of hard scaffolding is common in many engineering theory courses (e.g., statics, fluid mechanics). Alternatively, hard scaffolding might take form in an abstracted process model intended to guide students through a general framework for a particular type of problem; this form of hard scaffolding is exemplified by design process models used in engineering capstone design courses. Finally, soft scaffolding considers the nature and specificity of classroom discourse. For example, if the facilitator wants students to make consequential decisions and direct actions, then discourse between facilitator and students should support student autonomy (Mawer et al., 2024b; Reeve, 2016; Svihla et al., 2023). On the other hand, discourse that dictates specific actions among students would be expected in classrooms where the aim is to get everyone to the same solution along the same solution pathways.

The final stages are implementation and assessment. As in product and system design, the experience of stakeholders involved in these stages should be leveraged as an important feedback mechanism that informs the next generation of the problem experience. The design process of Figure 2 is an emergent one, stemming from our exploratory research. We see this process outcome as a valuable contribution to the practice of PBL and similar pedagogies, given extant challenges to those approaches described in the literature. However, we recognize a need to investigate this process in detail with other faculty, as discussed in later sections. In the next section, we describe the diagnose-and-solve learning experience that resulted from this process.

Final Design Solution

Prior to the diagnose-and-solve activity, students had engaged with two rocket-related problems (see Figure 1). Rockets were chosen over other aerospace systems due to students' greater familiarity with model rocketry, often gained through personal or school experiences, though not all students have such prior experience. Both problems were set within the context of the NASA Student Launch Competition using data and rocket designs contained in reports from the High-Powered Rocketry Club at the first author's institution. However, the High-Powered Rocketry reports lacked data on failed launches or unsuccessful design. As a result, we developed our own scenario and provided appropriate context. The resulting problem statement provided to students is provided in the Appendix.

Set the Problem Type and Context

Designing a diagnose-and-solve problem requires 1) an artifact that exhibits undesired performance, 2) data of the artifact's operation, 3) that students have the means to analyze the data, 4) that the students have the experience needed to understand their analysis and can identify the source(s) of undesired performance, 5) that the students have the means to create a solution to the proposed problem, and 6) that students have the means to determine whether a proposed solution addresses the undesired performance issue. Our problem aligns with a NASA Student Launch Competition requirement that participating teams engage in STEM outreach activities. The problem was based on field data collected during a middle school rocketry outreach event where students designed, built, and launched model rockets. The first author documented these launches with photos and videos. Though the rockets were amateur in nature, the data provided an authentic and relatable learning context, similar to how SpaceX learns from failed launches (Peterson and Mocko, 2024).

In K-12 education, rocketry is used to explore how forces act on a system, the design process, and iterative testing. While students are not typically expected to model performance or validate their designs, they do formulate hypotheses about observed failures (e.g., low altitude, parachute malfunction). The middle school students had been given, by their teachers, a set of requirements their rockets must satisfy:

- Rockets must use the teacher-supplied Estes B6-4 engine and recovery wadding
- Students must design and construct their own rockets (no pre-built kits are permitted)
- No more than one system component could be manufactured using 3D printing
- The rocket must at least reach a height of 50 feet

These experiences provide useful framing for undergraduates, who apply more advanced analysis and modeling techniques (linking conceptual and structural knowledge) and generate domain knowledge. While not all undergraduates have rocketry experience, they can relate to the middle school context and grasp the relevant science and math concepts. This familiarity may reduce intimidation and increase engagement with open-ended problems.

As a foundation for this problem, we selected a rocket that failed to meet the minimum height requirement and demonstrated an unstable flight profile. As shown in the diagnose-and-solve framework in Figure 3, students must first identify potential causes for a system's undesired performance. Conceptual knowledge is used to generate possible reasons that the system did not operate as desired. Through analysis, students validate these hypotheses and define new design requirements. This process culminates in proposing and testing modifications that address both technical and contextual constraints. As in many design problems, multiple feasible solutions may exist. Students must evaluate alternatives and justify their final recommendation using both qualitative and quantitative reasoning.

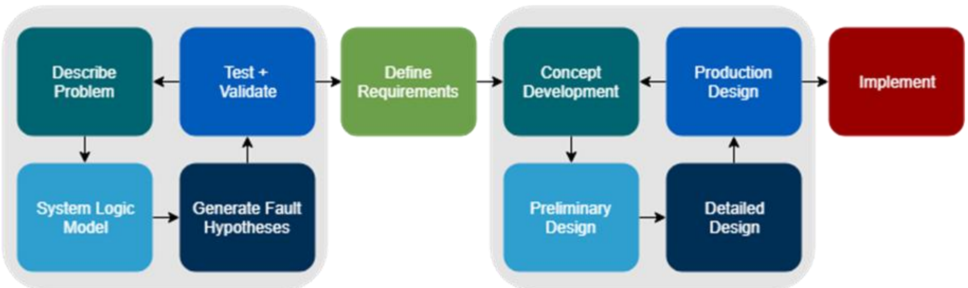

Figure 3. Problem Typology Framework for a Diagnose-and-solve Problem

Set Learning Outcomes

One challenge of setting learning outcomes for a diagnose-and-solve problem is avoiding unintended guidance that could shape students' thinking or prematurely suggest fault hypotheses. For instance, while a core objective of this problem is for students to understand how the center of gravity (CG) and center of pressure (CP) influence rocket stability, explicitly stating this may bias students' reasoning during the *System Logic Model* and *Generate Fault Hypotheses* stages of the framework (Figure 3). Learning outcomes span the various knowledge types:

- Students will be able to synthesize a redesign solution that addresses root causes (structural knowledge) while considering practical constraints (domain knowledge)
- Students will be able to articulate (domain knowledge) how their understanding of aerospace engineering concepts deepened through troubleshooting and redesign (conceptual knowledge)
- Students will be able to analyze forces acting on a rocket during launch and in flight (structural knowledge)
- Students will be able to construct a model that supports their analysis of the launch failure (procedural knowledge)
- Students will be able to formulate the requirements associated with a successful launch and translate them into design and manufacturing requirements (domain knowledge)
- Students will be able to estimate maximum altitude based on launch parameters using physics equations or simulation tools (procedural knowledge)
- Students will be able to test and refine their design modifications based on model predictions and feedback (procedural knowledge)
- Students will be able to explain the cause of the unstable flight (e.g., design, manufacturing, and operational factors) (conceptual knowledge) by analyzing launch data (structural knowledge) and applying their knowledge of rocket design principles (domain knowledge)
- Students will be able to communicate their redesign process and justification (domain knowledge)
- Students will be able to present their findings and proposed solutions in a technical engineering report or presentation (domain knowledge)
- Students will be able to engage in shared decision-making (domain knowledge) and divide tasks in their design iteration process (procedural knowledge)

Develop Problem Representation

We provided a pre-launch photo of the rocket that failed to meet the minimum height requirement and a video screen-capture of the rocket just after apogee, both shown in Figure 4. The full video of the launch, which shows the rocket spinning in the air uncontrollably before reaching apogee, was also provided to the students via the learning management system. So that the problem could be completed in the desired timeframe, students were given information about the dimensions and materials for the body tube, fins, nose cone, parachute, and launch lugs. This information was generated by graduate student L.

A clear, structured timeline was also provided. By the end of week 1, students were tasked with developing and documenting a plan of attack, guided by the process model in Figure 3. By the end of the second week, students were expected to describe their diagnosis and provide supporting evidence. They were asked to also provide their current strategy for solving the problem they identified. By the end of the third week, students were expected to describe their updated design and justify how it addressed the problem they diagnosed.

When the middle school students observed the unsuccessful rocket launch, they expressed a common belief that the nose cone's orientation caused the rocket's performance issues. This belief assumes the rocket's design was stable and that performance issues were solely due to construction errors. However, rocket stability is assessed using the concept of *static margin*, a dimensionless number found by dividing the distance between the Center of Gravity (CG) and the Center of Pressure (CP) by the body tube diameter. A rocket is considered stable when its CG is located ahead of its CP, with a recommended static margin between 1 and 2 body diameters. Although rocket stability is a foundational topic in most rocketry handbooks, many hobbyists and students are unfamiliar with the precise methods for calculating CG and CP. These calculations require knowledge of mass distribution and the rocket's geometry, including fin configuration. They are typically performed using hand-calculations (e.g., Barrowman equations (Barrowman, 1967)) or simulation tools like OpenRocket (OpenRocket, 2025) or RockSim (Apogee Rockets, 2025).

Figure 4. Left: A Model Rocket Designed and Constructed by a 7th Grade Student at a Local Middle School. Right: A Screen-capture of the Rocket a Moment After it Has Passed Apogee. The Video of the Launch Shows the Rocket Spinning in the Air Uncontrollably Before Reaching Apogee.

Pedagogical Reflection: Concept Map and Learning Hierarchy Analysis of the Problem

A concept map was developed to identify prerequisite knowledge (e.g., physics, geometry, aerodynamics) and locate areas where students may struggle or lack needed knowledge. A knowledge concept map for calculating static margin is shown in Figure 5. This problem requires conceptual knowledge of forces acting on the system, the concepts of center of gravity and center of pressure, knowledge that components have mass and geometry, and an understanding that static margin is used to assess stability in rocket design. This conceptual knowledge is brought together structurally in three major calculations: center of mass, center of pressure, and static margin. Procedurally, students must have knowledge of algebra and other mathematical operations, so that static margin can be calculated. Domain knowledge is specific to the field of aerospace engineering. Here, domain knowledge is that the static margin of the rocket should be greater than 1 and less than 3, as rules of thumb. As students and engineers gain experience designing and launching rockets, they develop a better understanding of how far these thresholds can be pushed. For example, students who had prior launch experience felt comfortable with static margins greater than 0.5 and considered this rocket "marginally stable". This structured overview was used to assess where scaffolding in the problem representation would have the greatest impact and benefit.

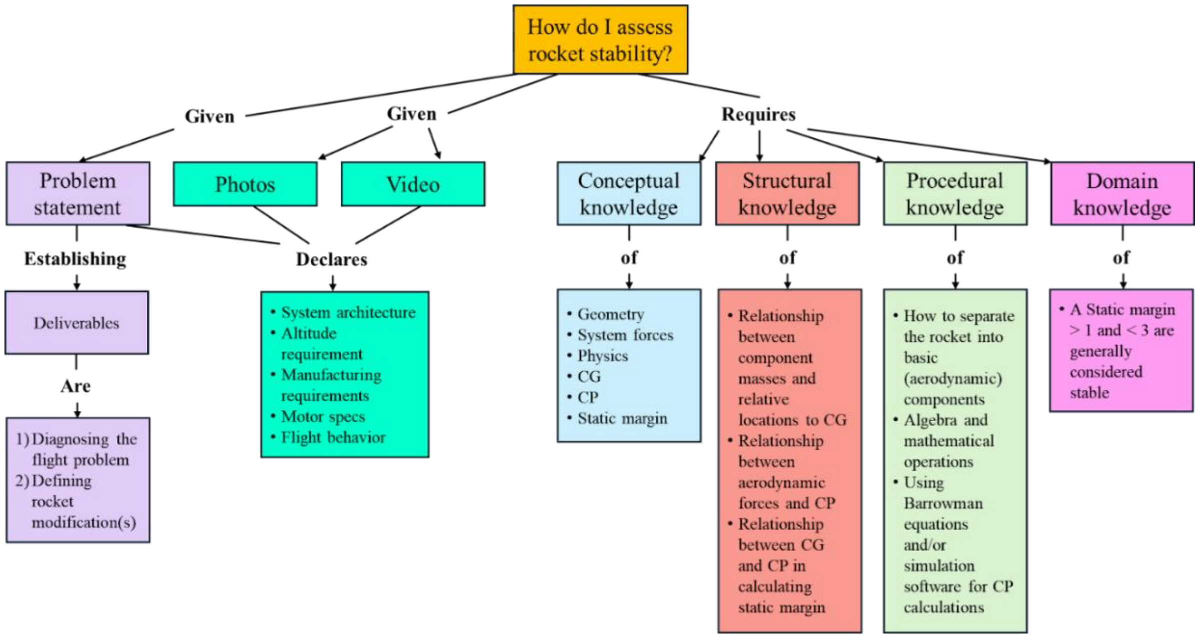

Figure 5. A Concept Map for Determining the Static Margin of a Rocket. All Four Knowledge Types are Needed to Calculate and Assess Static Margin.

We also constructed a learning hierarchy analysis, shown in Figure 6, to support problem facilitation. Ill-structured elements are highlighted in blue and complex aspects are highlighted in orange. Modeling the Center of Pressure is a complex element of this problem because there are various analytical and experimental approaches that can be used. Students must determine how the various components interact in defining a functional relationship to the center of pressure location. Unlike Center of Mass which is covered in multiple early engineering courses, Center of Pressure is a new concept in an introductory course that requires students to understand new relationships between rocket components. They must develop an understanding of how changes to each component propagate into a new Center of Pressure location. Assessing rocket stability is an ill-structured element of this problem because stability, in the context of static margin, is ambiguous. While there are established heuristics for static margin, it is up to the student to define an appropriate target value, and their calculation is subject to assumptions about rocket shape and configuration. Students must then address the complexity associated with modifying the solution. This requires generating feasible modifications and understanding how these changes integrate into the existing rocket architecture, taking into account the interdependent variables that influence overall system performance. After proposing possible design modifications, they must also engage in a down-selection process. From a complexity perspective, students must analyze and understand the relationship between parameters like thrust-to-weight ratio, static margin, apogee, and launch velocity. Tradeoffs, constraints, and manufacturing requirements must be considered. There is also an ill-structured element of this down-select process, as students must define a formal (or informal) value function to rank alternative solutions. This often involves subjectively assigning weights to student-selected criteria.

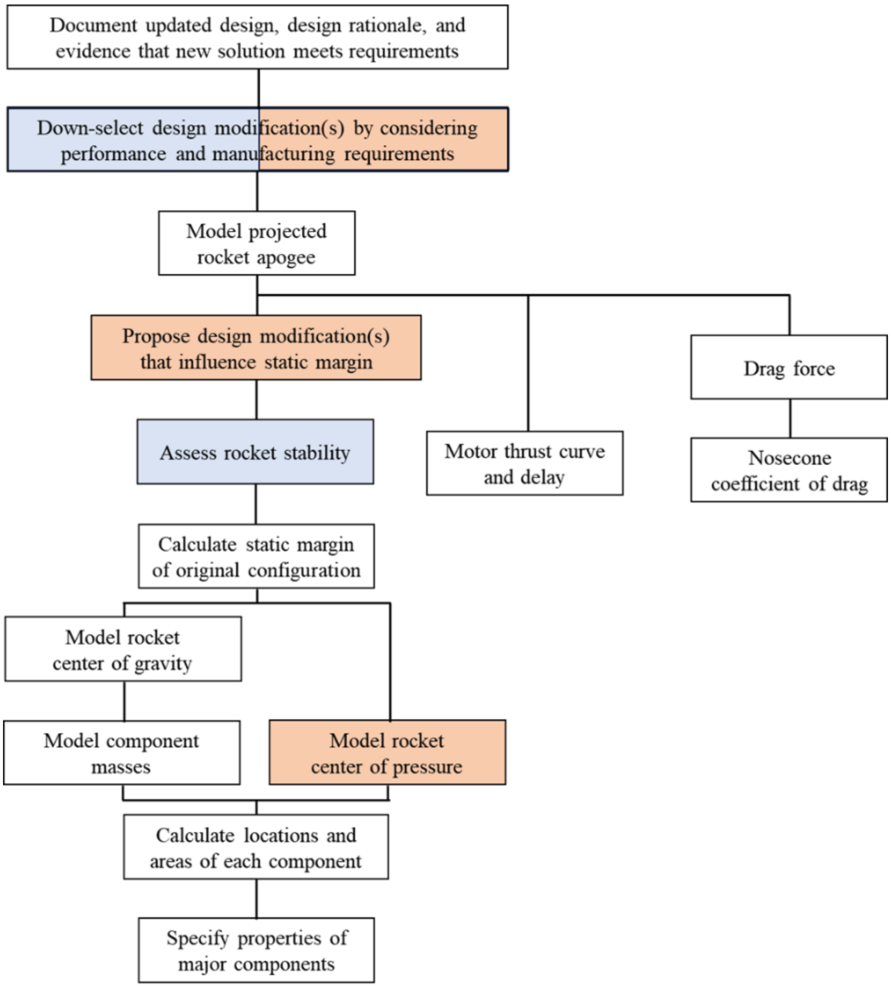

Figure 6. A Learning Hierarchy Analysis Used to Support Problem Facilitation. Ill-structured Elements are Highlighted in Blue, and Complex Aspects are Highlighted in Orange.

Devise Facilitation Strategy

To help students reason through how their proposed modifications affect system-level performance and stability, and in light of the three-week timeline, some problem elements were intentionally scaffolded to ensure students could meet the learning objectives. To reduce cognitive load and support student understanding, footnotes were embedded in the problem description [see Appendix]. These footnotes are linked to reference materials on rocket forces (Hall, 2023a), motor characteristics (Estes Education, 2025), and rocket stability from NASA (Hall, 2023b) and the National Association of Rocketry (Weber, 2012). Design constraints were also introduced to maintain problem boundaries: students were not allowed to change the body tube's diameter and had to retain at least two original components (e.g., fins, body tube, or nose cone).

Finally, students were encouraged to use computational tools to manage the complexity of performance analysis. With a defined rocket configuration, free software such as OpenRocket enabled students to calculate static margin, estimate apogee, and assess how performance changed with design modifications. These tools were introduced and discussed during in-class group facilitation sessions.

Problem Design Lessons Learned

Five key themes emerged from our experience of designing and implementing this diagnose-and-solve problem. First, valuable and data-rich problems can be sourced from everyday experiences and educational partnerships when instructors remain open and resourceful. Second, concept maps and learning hierarchical analyses provide tools that guide problem design, facilitation, and assessment. Third, ill-structured and complex problems provide facilitation opportunities that allow instructors to provide nudges in how students apply their quantitative reasoning during the diagnose phase. Fourth, the solution phase requires that students apply both qualitative and quantitative reasoning, particularly while resolving the complexity and ill-structuredness of down-selection. Finally, assessing learning in these contexts remains complex, particularly when students enter with diverse backgrounds and when key aspects of this learning process are not easily captured through conventional assessment artifacts. The following discussion elaborates on each of these themes, highlighting the opportunities, and implications for engineering education and the design of ill-structured and complex problems.

Sourcing Problems from Everyday Experiences and Varying Educational Levels

Diagnosing problems and developing effective solutions are foundational to the engineering profession. Yet, replicating this process in the classroom is not straightforward. Instructors must identify problems that are both authentic and accessible to students based on their current knowledge. If the problem is too advanced, students become frustrated; if too simple, they miss out on meaningful learning and skill development. Authentic engineering problems typically require rich data sets for analysis, modeling, and iteration. However, faculty members often lack access to proprietary or detailed real-world data. Even when usable data is available, it requires significant effort to clean, contextualize, and adapt for classroom use. Additionally, many educational settings lack the simulation tools and testing environments essential for validating engineering solutions.

Despite these challenges, valuable and engaging problems can be found in everyday life if educators are open to recognizing and harnessing them. The prior rocketry problems were developed through conversations the first author had with senior undergraduates and graduate students who were completing their capstone projects and were involved in student clubs. They provided access to data sets and prior reports. The data for this diagnose-and-solve problem was serendipitously captured by the first author because his son had, a month earlier, taken part in this middle school project. This middle school has embraced PBL, and for each PBL experience the teachers arrange for a subject matter expert to talk with the students. The first author volunteered as a subject matter expert and recorded rocket designs and performances to help facilitate next year's design-build exercise. This experience highlights the potential for symbiotic educational relationships. Middle school students explored a design problem that, for them, was ill-structured and complex. Though their rocket underperformed, the data they generated offered undergraduates a real-world case to diagnose-and-solve. These redesigns could then be shared back with the middle school students for further testing. As problems grow more complex, students at higher academic levels can contribute domain expertise and advanced analysis, enriching the learning experience for all involved.

Concept Maps and Learning Hierarchies Support Problem Design, Facilitation, and Assessment

Faculty can solve structured, closed problems before assigning them to students. As these problems often have a single solution pathway, there is a linearity in the problem-solving process that faculty can follow to ensure the problem "works" and to identify where students may face challenges. Ill-structured and complex problems, however, have multiple solution pathways and multiple acceptable solutions. The openness of these problems adds to the complexity of design ("what will the students need to do?"), facilitation ("how will I help them get, or stay, on a productive solution pathway?"), and assessment ("how do I grade and provide feedback about how successful they were?"). Knowledge concepts maps provide a tool for abstracting a problem and thinking about how elements are connected by considering the different types of knowledge that the students must bring to bear when engaging with a problem. This helps the problem designer assess whether students have the necessary foundational (conceptual) knowledge needed to understand the problem statement. In our problem, we provided footnotes to key conceptual elements of the problem for those students who had no prior rocket experience or who had not had more formal rocket education in their prior science courses.

This map also helped us identify what needed to be provided in the problem representation and where students would need to transition from procedure (calculating the static margin) to domain knowledge (assessing whether the number they calculated was acceptable or unacceptable). Knowledge concept maps informed the development of the learning hierarchy analysis. Here, we could identify which aspects of the problem required students to resolve ill-structuredness and/or complexity and understand where this occurs in the problem-solving process. Given the three-week timeframe for this problem, resolving the complexity of calculating the Center of Pressure could be assisted by making students aware that computational tools exist for this process and nudging them in this direction. Learning hierarchies also provide a foundation for developing assessment strategies by helping the instructor identify key elements of resolving ill-structuredness and complexity throughout the problem. However, more work in the area of assessment is needed to operationalize this resolution.

Scaffolding the Development of Quantitative Reasoning Skills in the Diagnosis Phase

Connecting experiential domain knowledge with formal engineering methods is critical for helping students move beyond intuition to deeper understanding. Both the middle school and undergraduate students observed that the rocket's failure was related to some aspect of stability. However, while they could describe *what* went wrong, they struggled to describe *why* using engineering principles. The first author interacted with many undergraduates who initially suggested the orientation of the nose cone was the main source of the failure. This presented a teachable moment and key facilitation touchpoint. Building on their intuition, the first author asked them "What if the nose cone were perfectly straight? Would that resolve the problem? If not, what else might explain the issue?"

This nudge prompted them to reconsider their assumptions and shift toward a more analytical mindset; an important opportunity to experience the qualitative to quantitative transition that is a hallmark of engineering practice. The next challenge was guiding students toward engineering tools that could help them test their hypotheses. Few students had experience using rocket-specific simulators or aerodynamic modeling tools. Introducing these tools through facilitation allowed students to begin exploring how professional engineers might evaluate rocket performance. Though most will encounter full-featured simulation environments in their upper-division courses, this experience gave them an early glimpse into how quantitative methods and tools can be used to explore the validity of qualitative reasoning (i.e., observation and intuition).

Solution Development Exercises Quantitative and Qualitative Reasoning

Once students identified that static margin was the root cause, they began proposing engineering modifications to address the issue. This involved both conceptual reasoning and practical problem-solving. Students' solutions largely centered on three core modifications: increasing the size of changing the placement of the fins, lengthening the rocket body, or adding mass toward the nose. Each modification reflected a basic understanding of the aerodynamic and mass properties that influence stability. For instance, increasing fin size or repositioning them rearward would move the Center of Pressure backward, while adding mass to the nose would shift the Center of Mass forward. Extending the rocket body could influence both parameters, depending on the design.

Students had to reason through the tradeoffs associated with each option. Adding nose weight, in the form of ballast, was conceptually simple and relatively easy to implement. Excessive mass, however, could negatively affect altitude and acceleration. Enlarging or repositioning fins could improve stability but would also increase drag and require precise manufacturing. Extending the rocket body tube introduced new fabrication challenges, especially given the materials available. These considerations prompted students to weigh the feasibility of each option, not only from an engineering analysis perspective but also in terms of what relevant stakeholders (7th-grade students) could realistically build and test with available materials.

Throughout this process, students applied both quantitative and qualitative reasoning. They used static margin calculations, obtained from their OpenRocket models, to estimate how proposed modifications would impact stability. Simultaneously, they relied on qualitative insights drawn from intuition, prior experience, and peer discussion to assess manufacturability, material constraints, and the likelihood of 7th-graders being successful at making the proposed modification. There was also a desire to pursue 3D printing options, specifically for the nose cone, as it added the ballast to the front of the rocket while also being 'cool'.

This phase of the problem marked a key turning point where students bridged formal engineering knowledge with design (i.e., the "solve" side of diagnose-and-solve). Their recommendations balanced technical rigor with practical constraints, resulting in solutions that were not only theoretically sound but also implementable by middle school students. In doing so, students engaged in authentic engineering practice of using analysis to inform design decisions while accounting for real-world limitations.

The Complexity of Assessing How Students Resolve Ill-structuredness and Complexity

Assessment remains a challenging aspect of this instructional approach. Qualitative observations and in-the-moment conversations suggest that the students found the experience engaging and valuable. However, the artifacts they submitted, such as slides, reports, and mathematical models, did not explicitly communicate how they recognized or reconciled the problem's ill-structuredness and complexity. It remains unclear whether these aspects of engineering thinking were salient to students during the process, or whether they simply lacked the tools or prompts to express this reasoning using conventional deliverables. Assessment strategies should help uncover how students identify, navigate, and resolve complex and ill-structured problems. This may involve using methods like reflective writing, structured peer dialogue, or think-aloud protocols that capture not only what students do, but how they reason through uncertainty. Understanding whether students can recognize (ill-)structuredness and complexity as salient facets of problems is critical to understanding their ability to transfer these higher-level forms of reasoning to new contexts and the long-term impact of such learning experiences.

Students also arrived with varying levels of prior experience and knowledge. This shaped how they interpreted the problem and the solutions they proposed. This further complicates assessment, as it can obscure whether a student's performance reflects learning from the activity or their application of pre-existing knowledge. It also raises questions about how to fairly and meaningfully evaluate student work when learners begin at different starting points. Traditional grading approaches, which often rely on standardized criteria or benchmarked outcomes, may not capture the depth or significance of individual student growth. Measuring progress toward mastery becomes especially challenging when mastery itself is a moving target and relative to each student's baseline. Assessing whether students have meaningfully advanced in their ability to reason through complex, ill-structured problems requires flexible and holistic developmental approaches that prioritize growth and process over fixed outcomes.

Conclusions

We described the development of a diagnose-and-solve problem for an introductory aerospace engineering course, following the structure of a design case. Our problem was informed by field data from a middle school outreach event and constructed to include both fault identification and a redesign element. Sophomore aerospace engineering students were presented with an engineering scenario where an amateur rocket failed to meet a launch height requirement. Students were provided with a picture of the rocket, a video of the flight, and information about the major components. This problem required engineering analysis to validate the fault hypothesis that the rocket was inherently unstable, regardless of any apparent manufacturing defects. Once the fault had been verified, students proposed rocket modifications that would address this fault so that the launch height requirement could be satisfied. We present this design case to the community because designing ill-structured, complex, and authentic problems can be challenging and time consuming. We found significant value in using a problem typology framework, knowledge concept maps, and learning hierarchical analysis as a way of working through problem design, facilitation, and assessment. From a problem design perspective, knowledge concept maps provide a way for the designer to consider what knowledge (across different types) students must have to fully and successfully engage with the problem. Learning hierarchy analysis offers facilitators a reflective tool for mapping how students might progress, supporting identification of the where and how ill-structuredness and complexity must be resolved, informing soft scaffolding accommodated through classroom discourse between facilitator and students. Problem typologies provide a hard scaffold to guide student thinking (e.g., identifying and validating a fault before proposing a solution) and high-level planning discussions between facilitator and students. Overall, the integration of these approaches provides the basis of a problem design process.

During implementation of this problem, we found that students were capable, with some facilitation, of resolving the ill-structuredness and complexity highlighted in Figure 6. Importantly, students' engagement in the problem did not require a lecture and demonstration of what assumptions to make or equations to use in modeling. Rather, students learned through facilitated engagement. The use of computational tools allowed students to test hypotheses important to diagnosing possible failure mechanisms and predict performance of proposed design modifications. Many groups redesigned the rocket so that design parameters fit within ranges consistent with theory reported in the literature. Groups with members who had prior rocketry experience were able to push the limits of their designs to achieve better overall performance. However, the expression of domain knowledge and justifications related to the resolution of ill-structuredness and complexity were not well documented in technical communications. Often, groups included drawings, equations, code, and figures without providing context that explained where assumptions had been made or what those assumptions were. This disconnect highlights the assessment challenge described previously. Though students appear to be constructing relevant knowledge (i.e., learning) while engaging the problem, the extent to which they recognize that learning is not fully evidenced. This issue suggests an important line of future work focused on understanding the extent to which students recognize ill-structuredness and complexity as salient aspects of a problem to be resolved through knowledge construction and evidenced through effective technical reporting. Further, the extent to which students' recognition is aligned with that of facilitator (domain expert) is an additional area for investigation as it might inform discourse norms for more effective classroom discussions, as well as pedagogical training that increases the adoption of ill-structured, complex, authentic problems in engineering classrooms.

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Appendix. Problem Statement

Teams entering the NASA Student Launch activity must satisfy a STEM Engagement requirement [Information on the STEM Engagement requirements are found of page 43 of this handbook: Handbook (https://www.nasa.gov/wp-content/uploads/2023/08/2024-sli-handbook-final-copy1.pdf)]. Satisfying this requirement involves engaging a minimum of 250 participants in direct educational, hands-on science, technology, engineering, and mathematics (STEM) activities. To address this requirement, your team reached out to a local middle school and worked with three 7th grade science teachers.

The teachers educated their students about the forces acting on a rocket [You can learn more about the forces on a rocket here: Forces on a rocket (https://www.grc.nasa.gov/www/k-12/rocket/rktfor.html)] and how those forces relate to Newton's Laws. They also watched one or two videos of model rocket launches. After learning about these concepts, the 7th grade students were assigned to groups and their teachers asked them to construct their own model rocket. Student groups were given multiple days to design and fabricate their rockets. Students were given the following requirements when designing and fabricating their rockets:

- Rockets must use the provided Estes B6-4 engine [You can learn more about this rocket engine here: B6-4 engine (https://edu.estesrockets.com/products/b6-4-engines)]
- Designs must use the recovery wadding provided by the teacher
- Students must design and construct their own rockets (no pre-build kits are permitted)
- No more than one component of the system must be manufacturing used 3D printing
- The rocket must reach a height of 75 feet

One of the student-group designs is shown in the picture to the right. Before students could construct their rocket, they had to produce drawings where they identified the dimensions and materials of major components. From these drawings, you know the following:

- Body tube
    - Material: Bounty paper towel tube roll
    - Length: 20 cm
- Fins
    - Number of fins: 4
    - Material: Cardboard
    - Height of each fin: 8.25 cm (along the body tube length)
    - Length of each fin: 6.5 cm (perpendicular to body tube)
    - Thickness of each fin: 0.25 cm
    - Placement: 1 cm above the bottom of the body tube
- Nose cone
    - Material: Construction paper
    - Shape: Conical
    - Length: 9 cm
    - Base diameter: Approximately 4.5 cm

- Parachute
  - Material: Crepe paper
  - Packed diameter: 4 cm
  - Packed length: 6 cm
  - Location of parachute: 2 cm from the top of the body tube
- Launch lugs
  - Material: Plastic straw pieces
  - Number: 2

This design and fabrication process culminated in a launch event where each group had the opportunity to test their rocket. The rocket engine is secured in the rocket body by an engine mount that is constructed by the students and the teacher. This engine mount consists of layers of rolled cardboard that are inserted into the bottom of the rocket. The mount is glued in place the day before launch.
Launch day was sunny with minimal wind. A video of the rocket launch is posted on Moodle.

This launch was … not particularly successful. This rocket whirls around in the air uncontrollably [You can learn more about rocket stability from NASA (https://www.grc.nasa.gov/www/k-12/rocket/rktstab.html) and from the National Association of Rocketry (https://www.nar.org/nar-products/rocket-stability/)]. I have taken two snapshots from the video and have included them below.

Objective

As part of your STEM engagement activity, you are going to help the students understand what went wrong (diagnose) and then redesign this rocket (solve) so that a launch can be achieved that meets the stated mission requirements. In a diagnose-and-solve problem, you must troubleshoot and then identify/select the alternative solution that will eliminate the identified fault states.

However, I do not want you to completely scrap their original design. You must:

- Not change the diameter of the body tube so that the engine mount does not have to redesigned
- Reuse at least two of the following components in their original form (fins, body tube, nose cone)

Deliverables

Your task is two-fold. You must first diagnose the issues with the original design. Then, you must generate a solution that overcomes (solves) this issue such that a successful launch can be achieved.

Your submission (final report) for this problem will be a documentation of your process. You will:

- Describe the problem
- Generate fault hypotheses
- Test and validate the fault hypotheses, arriving at a final argument for what happened
- Develop concepts that will fix the proposed rocket solution
- Select the concept that you will validate
- Validate the selected concept to show that your proposed solution meets the mission requirements

Timeline of the problem and submission requirements

- **Week 1**
  - Individually, draw a diagram that represents the problem-solving process that you think you should follow. Provide a description for each process stage in your diagram. Please do not spend more than 15-20 minutes thinking about, drawing, and reflecting on this diagram.
  - Work on the problem in-class
  - The expectation is that each student will spend 1-2 hours outside of class working on this problem. Partition the upcoming effort so your group works effectively.
- **Week 2**
  - Work on the problem in-class
  - The expectation is that each student will spend 1-2 hours outside of class working on this problem. Partition the upcoming effort so your group works effectively.
- **Week 3**
  - Finalize your group's work by documenting all efforts made in solving this problem.
  - One of your group members must submit your work to the submission link on Moodle.