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Unpacking Capabilities Underlying Design (Thinking) Process*

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Engineering graduates must know how to frame and solve non-routine problems. While design classes explicitly teach problem framing and solving, it is lacking throughout much of the rest of the engineering curriculum and is often relegated to capstone classes at the end of the students' educational experience. This paper explores problem framing and solving through the lens of experiential learning theory. It captures core problem framing and solving approaches from critical, design and systems thinking and concludes with a table of learning outcomes that might be drawn upon in designing an engineering curriculum that more fully develops the problem framing and solving capabilities of its students.

Keywords: problem framing and solving; design thinking; design process; engineering education; learning outcomes

1. Introduction

Design process, particularly in the form of design thinking, is spreading within engineering curricula as educators explicitly teach design principles and embed design thinking into project-based classroom experiences. Design thinking, it is argued, provides students with creative methods to grapple with complex problems [1], and serves as a complement to rational and analytical approaches conventionally taught in engineering schools [2, 3]. While design process has been taught for years in courses on new product development, the popularity of design thinking and the increasing need for engineers to engage in creative engineering problem solving [3] is now causing design approaches to be introduced in a wider variety of settings, both curricular and co-curricular.

This is often, however, being done without close examination of the types of problems engineers are called upon to solve and thus what problem framing and solving approaches need to be developed, how they might best be developed, and under what circumstances they should be used. This paper uses a framework grounded in learning theory [4] to examine the capabilities that engineering students need to develop to effectively frame and solve problems. The framework is used to review not only design process or thinking, but also critical thinking and systems thinking as approaches for framing and solving problems in engineering disciplines. This work sits in a space of broader concern: in short, college students show remarkably low gains in critical thinking, complex reasoning and written communications during their college years [5].

This paper aims to shift the current conversation from "How might we further disseminate design thinking or design process?" to "How might we best prepare engineering graduates to frame and solve the variety of problems they will face in their future work?". It proposes a draft set of learning outcomes that may provide a foundation for course design that integrates learning about problem framing and solving more broadly into engineering courses, not just those on design.

2. Problem Framing and Solving Capabilities

In engineering education and practice, there are still routine problems for which known solutions can be applied to well-understood problems. Routine problems are readily addressed through the acquisition of *declarative* knowledge (facts, things), *procedural* knowledge (competencies, skills) and *conditional* knowledge (understanding when, why). However, there is a growing number of situations in which creative engineering problem solving is needed, including: when a new solution satisfies an old problem, but does so better, faster or cheaper; when a new solution opens possibilities thus satisfying a new problem; and when a new problem can only be satisfied by a new solution [3]. To tackle non-routine problems, students must develop *functioning* knowledge, or the ability to apply facts and skills in an appropriate manner [6]. Functioning knowledge requires a solid foundation of declara-

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tive, procedural and conditional knowledge *and* the ability to draw from and appropriately apply that foundational knowledge to generate novel and effective solutions to non-routine technological problems [3]. This requires the development of problem framing and solving capabilities that complement the linear analysis-synthesis sequence taught in many engineering classes and include the generative and iterative approaches drawn from design, creative problem solving and systems thinking [7].

There is a rich history of research on learning to draw upon to understand how to teach students to frame and solve problems [8, 10]. As in prior research on engineering education [11], this paper uses experiential learning theory [12] to bring alive the core elements of design (thinking) [4] and make connections to cross-boundary teaming [13]. Experiential learning theory [12] describes how we take in and process information: We take in information along a spectrum from concrete experience to abstract conceptualization, and process information along a spectrum from reflective observation to active experimentation. Four core capabilities are framed by this model (Fig. 1): *Observe and Notice*, which happen at the intersection of concrete experience and reflective observation (e.g., when students observe use of technology in context); *Frame and Reframe*, which happen at the intersection of reflective observation and abstract conceptualization (e.g., when students see a different way to look at a situation or a new aspect of a problem); *Imagine and Design*, which happen at the intersection of abstract conceptualization and active experimentation (e.g., when students creatively identify alternative solutions or ways of addressing a problem); and *Make and Experiment*, which happen at the intersection of active experimentation and concrete experience (e.g., when students translate ideas into physical representations or conduct experiments to test a hypothesis) [4]. Learning entails cycling through the model: observing and noticing; abstracting from that to frame and reframe; using the new frames to imagine and design alternatives; and making or building alternatives to experiment with them in the concrete world.

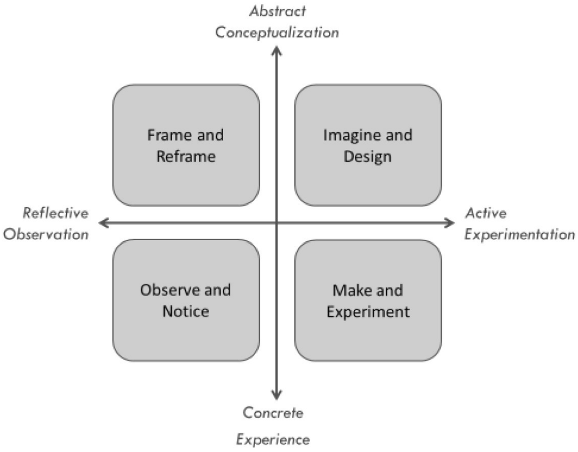

Fig. 1. Design Thinking as a Learning Process adapted from [4].

Reflective observation work – *Observe and Notice* and *Frame and Reframe* – entails problem structuring [14] or problem framing [15] and focuses on understanding or knowing. Active experimentation work – *Imagine and Design* and *Make and Experiment* – involves solution creation and is focused on creating and doing [16, 17]. Effective learning, and by extension effectiveness at grappling with complexity, requires students to have competency in both problem framing and problem solving.

The following sections unpack the four core capabilities of problem framing and problem solving in turn, capturing how design, critical and systems thinking intersect with them and exploring connections to engineering approaches to framing and solving problems. There is precedent for imagining such integration: John Arnold saw creative thinking as a synthesis of analytical, judicial and synthetic thinking [18]. Design thinking and engineering systems thinking are seen as complementary approaches to understanding cognition, organization, and other non-technical factors that influence engineering design and performance [19]. Creativity, sometimes described as the heart of design thinking [18], is seen as critical to engineering work and yet better understanding of how and where it might be taught in the engineering curriculum is needed [3, 20].

2.1 Problem Framing

Problem framing, employing *Observe and Notice* and *Frame and Reframe* capabilities, may be the most critical part of a design process [15, 21, 22]. Engaging students in problem framing – not just problem solving – is seen as a significant gap in engineering education [3, 20, 23]. Although emphasis is given to the activities in *Imagine and Design* and *Make and Experiment* in many practitioner descriptions of design thinking, the literature on designerly thinking (i.e., practices rooted in the academic field of design) recommends more balanced distribution of effort among the four quadrants of the experiential learning model [24] and particularly to the critical sensemaking efforts that result in deep understanding of the problem to be solved. Sensemaking requires gathering all available knowledge bearing on how a solution is planned, and coming up with working hypotheses for exploration and development [7]. It sets the stage for the divergent thinking needed to generate alternative solutions [3].

Examples of ways in which engineering students might employ problem framing skills include: when students are asked to disassemble a product, identify its components, map their interactions and then reassemble the product; when they are asked to visit the context in which a technology or product is to be used; or when they observe the behavior of a system to understand where a technology might best be deployed to improve its performance. In short, problem framing skills are leveraged whenever students engage with the concrete world in service of identifying an appropriate frame for a problem they aim to tackle.

The act of framing in practice is both a cognitive device and a communicative activity defined by selection, emphasis, interpretation, and exclusion [25]. Importantly, relative to understanding design as meaning-making [24], framing is the ability to shape the meaning of a subject, to judge its character and significance. Framing requires skills in communicative goal setting, developing mental models, figurative language use, context sensitivity, and priming for spontaneity [26]. Here we unpack the two capabilities associated with sensemaking: *Observe and Notice* occur in the concrete world while *Frame and Reframe* take place in abstract space. Both involve reflective observation in an iterative act of taking in information and reflectively processing that information to see a situation in different ways. Diversity in perspectives [27] on a team is critical in this phase to provide multiple views for the interpretation of inputs.

2.1.1 Observe and Notice

Observe and Notice happen at the intersection of concrete experience and reflective observation. Associated skills include viewing concrete situations from multiple points of view, having broad cultural interests, listening with an open mind to different perspectives, and being imaginative and emotionally connected [12].

Critical thinking emphasizes sensing or taking in data (*Observe and Notice*), perceiving or interpreting the data and then drawing conclusions (*Frame and Reframe*); poor observation leads to faulty thinking regardless of how well one reasons [28]. Being astute observers requires putting aside biases, actively listening, asking open-ended and probing questions, and eliciting and capturing stories [29]. It also means looking at data with a critical eye, carefully forming hypotheses about causal relationships. "In its exemplary form, it is based on universal intellectual values that transcend subject matter divisions: clarity, accuracy, precision, consistency, relevance, sound evidence, good reasons, depth, breadth, and fairness. . ." [30]. Just as the beginnings of science are always the capacity to be able to be amazed by apparently simple things [31], the beginnings of critical thinking are the ability to see the often obvious and simple things that structure human experience [32].

Systems thinking, a broader view of engineering systems thinking [19], is also grounded in observation as it requires observing events or data to identify patterns of behavior over time [33]. A systems thinking perspective requires a mindset of curiosity, clarity, compassion, choice and courage [34]. Techniques such as interviews and observation are used in systems thinking to learn about enablers and inhibitors of system behavior and the underlying structure of a system [35]. Systems thinking calls upon both qualitative and quantitative sensemaking skills.

Design thinkers use *Observe and Notice* to know the context and people associated with the space in which their innovations will exist. They do so by paying attention broadly to political, economic, social, environmental, technical and other trends [23], and immersing themselves with customers, users and other stakeholders to develop deep understanding of behaviors, attitudes, aptitudes, challenges and motivations of others in the context of their lived experiences [7, 17]. This is accomplished by spending time with customers and users, observing and conducting interviews with them to explore their physical and social interactions, cognitive processing, cultural experiences and norms, and emotions [17, 36].

Social skills associated with *Observe and Notice* are increasingly important, as other skills are easier for machines to replicate. They include the ability to attribute mental states to others based on their behavior, or more colloquially to 'put oneself into another's shoes' [37]. Note that *Observe and Notice* skills are useful not only for understanding customers, users and other stakeholders, but also for understanding colleagues in the workplace.

Why do engineers need to learn both the qualitative and quantitative skills associated with *Observe and Notice*? (1) Engineers need to understand the world in which they will deploy solutions so that they can anticipate and manage negative or unintended consequences. By learning about political, social, environmental and economic trends and systems, engineers can consider the interactions of their work outputs with broader society [23]. To gain such understanding, students might be required to do some trends research online and then digest what they have learned with their peers seeking new opportunity spaces. (2) Engineers need to understand people and the problems they are solving for those people so that they can engage in empathic design [38, 39] to develop impactful solutions. This could involve interviewing or observing people facing the challenge they are working on. (3) Engineers need to understand the landscape of available technologies to inspire thinking about alternative solutions. As James Dyson describes ". . . I do go around looking at things critically to see if it's a good idea or if there could be an improvement . . . really, almost all engineers do that. If you don't you are not really an engineer" [40]. The sharing of artifacts, ideas and know-how at Maker Faires [41], IDEO's Tech Box and the TRIZ-box formulation provide indications of ways in which engineers *Observe and Notice* available technologies [42]. To practice this, students might be exposed to a range of technologies and asked to describe their observations, create comparisons among them, or hypothesize alternative uses for them.

Questions remain: Where in the engineering curriculum should *Observe and Notice* capabilities be developed? Or might they be better developed through partnerships with other disciplines? How might their development – as declarative, procedural and conditional knowledge – be embedded in "traditional" engineering courses? How do we change the narrative around *Observe and Notice* capabilities so students have interest to develop them? How might their development be assessed over the life of an undergraduate or graduate program? How might they become valued as elements of core functioning knowledge for engineering graduates?

2.1.2 Frame and Reframe

Frame and Reframe happen at the intersection of reflective observation and abstract conceptualization. In this phase, one takes the messy data of *Observe and Notice* and tests it against existing mental models [43], generates new insights [17], and sets up the hypotheses or questions to be tackled in problem-solving. *Frame and Reframe* capabilities include the ability to understand a wide range of information and put it in concise, logical form, to explore analytical models and to take the time to think through problems to be solved and questions to ask.

Critical thinking advocates [28] practice *Frame and Reframe* by identifying facts (what's real?), inferences (what follows?), assumptions (what's taken for granted?) and viewpoints (what's the filter?). Reframing requires undoing the unconscious biases absorbed through deep life experiences and understanding one's own system of thinking [44]. Undoing requires the ability to evaluate information for relevance, construct plausible inferences, accurately identify assumptions, distinguish relevant points of view and parse significant from insignificant information [45].

Systems thinking also invites framing and reframing through systems visualization or mapping that allows for identifying patterns of behavior, enablers and inhibitors of change in the system and leverage points for creating change [33, 46]. How the system is perceived can vary according to how a given stakeholder is engaged in the system. Thus, systems thinking requires understanding the stakeholders involved, mapping system dynamics from the perspective of each stakeholder, and examining patterns of interactions to determine ways in which behavior of the system might be improved [47]. Taking a systems view of a situation may provide a different frame for a problem than taking a single point of view [48] as is often done in design thinking. ESTs [Engineering Systems Thinkers] ask 'good questions'; can understand new systems and concepts quickly; can consider non-engineering factors that influence system performance; and understand analogies and parallelism between systems [19].

In design thinking, *Frame and Reframe* require bringing structure to what has been captured in the *Observe and Notice* phase, including sorting, clustering and organizing the data using visualization tools such as affinity diagraming and customer journey mapping to surface interesting patterns or findings [17]. The work can be characterized as dimensioning and diagramming data, as well as challenging assumptions to open new possibilities [49]. Experienced designers tackle this phase by searching for a central paradox or attempting to identify what makes the problem so hard to solve [22]. The dominance of converging mindsets amongst engineering students and practitioners [50] and associated desire to move quickly to solutions often causes teams to minimize time spent in framing and reframing.

Development of problem framing skills is widely seen as lacking in the engineering disciplines [3, 51]. Students resist being asked to grapple with the ambiguity associated with *Observe and Notice* and *Frame and Reframe* but will have to do so on the problems they face upon graduation. Scant focus on problem framing is not unique to engineering education, as *Frame and Reframe* skills are not well taught in educational institutions more broadly [45] or well-practiced more generally in society [25]. Perhaps the greatest opportunity for reimagining engineering education is to develop students adept in understanding complex problems and identifying opportunities for change which requires a shift in focus from structure of thinking to quality of thinking [45]. A simple means of embedding framing opportunities into engineering classes is to refrain from giving students tight problem specifications. Instead of, for example, having them design a better plate to hold food and drinks at a recruiting event, ask them to identify the challenges associated with recruiting events. Rather than specify what function a turbine blade must fulfill, ask them to identify places where the functionality of turbine blades might be useful and then create a design.

Questions remain: How might we offer more opportunities for engineering students to engage in problem framing work in a wider range of classes [52]? Are there ways to develop *Frame and Reframe* capabilities, even as students are learning declarative and procedural knowledge? Which *Observe and Notice* skills will be most needed to facilitate engagement in *Frame and Reframe* work?

2.2 Problem Solving

On the problem-solving side of the learning cycle *Imagine and Design* entail coming up with options for addressing the problem as framed and *Make and Experiment* iteratively test generated options. While both framing and solving toggle between abstract and concrete worlds, problem solving requires active experimentation rather than the reflective observation of problem framing [12]. Finding an appropriate balance between problem framing and problem solving is often problematic. Lack of focus on problem framing or of access to information about a problem and its context can lead to making premature solution choices [53]. Designers in general are often accused of being solution-led, not problem-led [54]; designers with a problem orientation tend to iterate on requirements throughout the design process, while solution-oriented designers specify the solution at the beginning. While problem solving focuses on imagining and designing concepts or alternative futures and on making and experimenting with those ideas, engaging in problem solving often causes a team to question the frame driving the ideation. Letting a team explore multiple problem spaces is often a way to open their thinking about a potential solution space [55].

Problem solving skills could be invoked by asking students to identify alternative approaches to addressing a problem and/or asking them how they might test their approaches in the concrete world. They might be asked, for example, to identify all the ways to propel an object across a room, what the risks are with a solution they've created and how they might test those risks, or to list various environments in which a piece of code might be run and how they expect it will work in those settings.

At a fundamental level, problem solving consists of trial and error, directed by some insight as to where a potential solution might lie. Learning and improvement in organizations come primarily from the errors encountered through trying new policies, technologies or behaviors [56]. Trial and error, however, is best complemented by rigorous approaches to experiment design and execution [57, 58]. Here we unpack the capabilities that underlie problem solving: *Imagine and Design* and Make and Experiment.

2.2.1 Imagine and Design

The insights or principles derived from *Frame and Reframe* provide the basis for generating opportunities or concepts in *Imagine and Design* [22]. In this phase, focus shifts from reflecting to acting [12], from understanding to making [17]. Capabilities in *Imagine and Design* include the ability to find practical uses for ideas and theories, solve problems and make decisions based on finding solutions to questions or problems [12]. They also include being able to experiment with new ideas through simulations, laboratory experiments or returning to the field in a drive towards practical application.

Interestingly, in this phase design thinking and critical thinking complement one another as design thinking offers approaches to generating ideas while critical thinking provides logic-based approaches to converging around a smaller set of ideas. Diversity in heuristics (approaches to solving the problem) [27] on a team is critical in this phase to generate a breadth of ideas to address the problem space. When students, for example, share familiarity with a prototypical solution (e.g., an app) it is unlikely that they will conduct a sufficiently in-depth exploration of other options in the design solution space.

From a designerly thinking view, "Design is a unique type of problem solving. It is the maximum expression of human intelligence and the prototypical case of cognition, as it requires devising future states of the world (goals), recognizing current ones (initial states) and finding paths to bridge them (transformation functions). Moreover, it requires the generation of external representations of such states and paths" [14]. At a meta level, this characterizes the *Imagine and Design* phase.

At a practical level, design thinking bridges from *Frame and Reframe* to *Imagine and Design* with "how might we?" questions [59, 60] that frame a problem, often from a particular point of view (e.g., that of the customer), and open the space to generate ideas. Within this phase, individuals employ a variety of ideation techniques – many derived from brainstorming approaches introduced in the 1950s [61] – to diverge around or generate concepts for products, services, communications, environments, brands, customer experiences or business models, often simultaneously bringing those ideas alive through rough sketches or prototypes [62]. Using visual representations of concepts or ideas often facilitates combining and refining of concepts to generate additional ideas [62, 63].

Many idea generation techniques are identified and evaluated in the engineering literature, including morphological analysis, synectics, brainwriting, nominal group techniques, axiomatic thinking, theory of inventive problems solving and affinity diagramming [23, 64–66]. Similarly, multiple technologies are identified in the engineering literature for simulating and generating ideas, e.g., virtual reality methodologies facilitate considering realistic needs, visualizing scenarios and exploring design alternatives [23].

Critical thinking complements the divergent and generative thinking approaches offered by design with convergent thinking approaches. While designers advocate such tools as "dot voting" and other collaborative but largely gut-based means of narrowing a solution set, logic-based critical thinking provides other options well-captured in the engineering literature including the Pugh Controlled Convergence method, Quality Function Deployment and the Analytic Hierarchy Process [68] as well as concept screening and scoring [69]. The Pugh method has been shown to yield better results than other methods, in part because it allows for cycling through additional idea generation (diverging), thus enhancing or further developing ideas [70].

Systems thinking is increasingly being leveraged in this phase through the emergent field of transition design which first imagines transitions to sustainable futures and then enacts systems-level change [71]. The ability to envision and speculate about potential futures, core elements of scenario planning [72], is seen as a key component in bringing potential change to fruition.

The problem-solving phase is far better characterized in the engineering literature than the problem framing phase, although it is not clear to what extent the identified methods or approaches are embedded in classes other than those focused on engineering design. Further, in engineering much more focus is placed on converging than on diverging: "Academic excellence (at least in engineering) is synonymous with skill at convergent production, since engineering education (unlike engineering practice and life in general) normally involves only problems with single correct answers" [52]. Seemingly few engineering courses teach directed metacognitive activities related to creativity or the development of new ideas, in part due to lack of instructional materials, limited time or lack of understanding about how to teach them [73]. How might more *Imagine and Design* work be built into foundational engineering learning? In what ways might students be encouraged to explore alternative options or answers to problems before converging?

2.2.2 Make and Experiment

While *Imagine and Design* work is conducted largely in abstract space, *Make and Experiment* require that solutions be purposefully built and tested, allowing for learning through hands-on experience. Experimentation is well understood as a fundamental innovation activity, a form of problem solving, and a significant part of innovation cost and time that spans a variety of modes such as computer simulation, mass screening, and rapid prototyping [45]. Considerable research has explored approaches to experimentation used in practice, for example, conducting parallel versus sequential tests [74], the amount of time dedicated to testing [75] and the types of organizational changes required to adopt different approaches to experimentation [76]. Skills to be developed in the *Make and Experiment* phase include being able to identify key elements of a solution to test, to creatively design ways of testing, and to actively listen and adapt in response to the feedback received.

From an analytical perspective, and particularly well-articulated in scientific process [77], at the core of *Make and Experiment* is the ability to identify key hypotheses or risks that are to be evaluated before constructing the solutions or experiments to be run. There are myriad approaches to doing so in the engineering literature and elsewhere including Analysis of Competing Hypotheses [78] and Design of Experiments [79]. Facilitated by technology, experimentation at scale is now possible and employed widely, particularly in software-based companies [74]. Some of the technologies that make rapid experimentation possible include virtual reality, machine learning, axiomatic design, and simulation [23]

Systems thinking tests the validity and robustness of systems models created during the problem framing work, with particular attention to how closely those models represent reality [80]. As the ultimate objective of systems thinking is to create changes in the behavior of a system (and the people within the system), experiments are conducted to determine whether or not a hypothesized change creates the desired outcomes [81]. Given a core principle of systems thinking is that "parts of a system only have meaning in their relation to the entire system", [82] experiments are also used to understand the nature of interdependence. Probing the system allows one to assess types of unexpected reactions that occur when a change is implemented.

Design thinking prioritizes rapid prototyping, bringing ideas alive and then taking them out into the concrete world, testing and getting feedback from real potential customers, users, and other stakeholders. It aims to test solutions along three dimensions: desirability, feasibility and viability [83]. The desirability lens questions how the user will engage with the product and whether the user will find the product compelling or desirable. The feasibility lens examines what is technically and organizationally feasible, and the viability lens asks about what is financially and economically viable for the company. Recent explorations suggest that there is much still to be learned about prototyping to explore the desirability of a concept, particularly for physical products [84].

As with *Observe and Notice*, the Maker community models some of the behaviors needed among engineering graduates to *Make and Experiment*. Makers share their outputs at Maker Faires, as Instructables project recipes, in articles for Make Magazine and the like. Iteration and sharing are simply a part of the Maker community [41]. At present, most courses involving *Make and Experiment* are electives, or occur late in the curriculum as capstone design projects. How might *Make and Experiment* become a more integral part of engineering education? What are the informal ways in which students might be encouraged to share, iterate and learn from one another? What formal experimentation methods need to be taught in which classes so that students might develop a deep understanding of structuring and learning from experiments? How might experimentation be framed less around failure and more about learning?

3. Discussion

This review, framed using experiential learning theory, explores the core capabilities underlying problem framing and solving drawn from design (thinking), critical thinking and systems thinking. It contributes to prior efforts to determine learning objectives for increasing design abilities and teaming/collaboration proficiency [85], to develop cognitive, metacognitive and affective learning activities [86], and to create more active methodologies in which to engage students [87]. These authors, however, focus on pedagogy design rather than on the creation of learning outcomes and content around problem framing and solving.

Table 1 summarizes a set of possible learning outcomes associated with framing and solving problems drawn from literature on design, critical and systems thinking. There are shared themes across the types of thinking that might allow for development of curricular components to progressively scaffold development of problem framing and solving skills in engineering students. Below are a few of the shared themes and examples of how they might be embedded in engineering courses.

Observe and Notice: Basic themes entail identifying and putting aside biases; listening actively and with an open mind; examining multiple perspectives; and engaging in the world with curiosity and compassion. Exercises to achieve these learning outcomes might involve asking students to identify instances of a topic (e.g., fluid dynamics, data analytics, sensor design) in context and describe elements of that context.

Frame and Reframe: Basic themes include identifying and discerning facts, inferences and assumptions; organizing information to make sense of it; seeking patterns in data; extracting meaningful conclusions; and constructing plausible inferences. Building upon their observation work, students might be asked to share their observations with peers (virtually or during in-class discussion), and asked to describe the importance of context for the analyses they are learning. In the process, they might be asked to identify assumptions they made about the importance and effects of context and then asked to make plausible inferences. Providing such opportunities for students helps them connect what they are learning to their everyday lives, and motivates them to learn the content being provided in the class [88]. Using analogies/metaphors to facilitate student understanding of new concepts might also be used at this stage [89].

Imagine and Design: Basic themes fall into the categories of diverging to generate options or alternative futures and then converging to select among them or creatively mixing and matching them to create better ones. Homework questions in which students suggest multiple ways to approach a technical problem or the opportunity for students to create final exam questions can facilitate development of divergent thinking. Having students share and process alternatives in class and then choose criteria (e.g., fluency, flexibility, originality) for identifying the best approaches can help them learn to converge without there being a single correct answer [52].

Make and Experiment: There is less commonality across types of thinking in this category than in others. The collective fundamental capabilities include identifying hypotheses or risks; creatively generating means of testing them; constructing and conducting tests or experiments; being open to failing and having to try again. (Note that this is an integral part of applying the scientific method [77], which could meaningfully be added to the learning outcomes table.) Having students build a design rather than leave it in conceptual form not only improves learning [90], but provides an opportunity for them to achieve *Make and Experiment* learning outcomes; Lab in a box [85], for example, provides students with a kit for conducting experiments during class.

Table 1. Learning Outcomes Associated with Problem Framing and Solving

	Experiential learning theory	**Design (thinking)**	**Critical thinking**	**Systems thinking**
Observe and Notice	View concrete situations from multiple points of view. Watch to gather information. Listen with an open mind to different perspectives. Develop cultural understanding. Connect emotionally with people, problems, and communities. Generate ways to see a situation.	Identify key stakeholders. Empathize with and understand stakeholders' lives. Observe and interview, asking open-ended and probing questions. Elicit and capture stories to uncover meaning-based needs. Understand trends.	Sense/take in data. Identify potential and unconscious biases. Determine strategies to undo biases. Listen actively. Examine data with a critical eye. Devise hypotheses about causal relationships.	Observing events or data to identify behaviors relevant to the system. Engage a mindset of curiosity, clarity, compassion, choice and courage. Recognize the interdependency of components within a complex system.
Frame and Reframe	Organize information in a concise, logical format. Explore analytical models. Test soundness of theories. Think through problems and questions to ask.	Structure, dimension, diagram (qualitative) data. Recognize users' core needs and priorities. Identify and challenge assumptions. Analyze trends. Reframe problems.	Perceive/interpret data: distinguish facts, inferences, assumptions and viewpoints. Determine relationships among data to find relevance and meaning. Construct plausible inferences. Draw conclusions. Parse significant from insignificant information. Integrate issues using other (disciplinary) perspectives.	Test new observed data against existing mental models. Map system dynamics from the perspective of each stakeholder. Identify components that make up a system by analyzing events and patterns. Identify enablers, inhibitors and leverage points for creating change. Illustrate interactions between the system and its environment.
Imagine and Design	Find practical uses for ideas and theories. Find solutions to questions or problems. Identify key hypotheses or risks. Experiment with ideas.	Diverge to generate concepts. Apply ideas from other sources to issues, ideas, artifacts, or events. Demonstrate openness to new ideas. Combine, refine and converge on concepts. Conceptualize ideas through rough sketches or mechanisms of visualization.	Connect concepts to additional application areas or hypothetical scenarios. Evaluate options methodically and analytically.	Envision alternative futures (systems changes) that lead to better or different systems outcomes. Generate alternative means of triggering systems change.
Make and Experiment	Carry out plans. Get involved in new and challenging experiences. Act on "gut" feelings. Rely on people for information (more than on technical analysis). Work with others.	Bring concepts alive through (rapid) prototyping. Gather feedback on concepts, preferably in context. Modify concepts based on feedback. Evaluate concepts for desirability, feasibility and viability.	Identify key risks to be evaluated. Synthesize and present thoughts in new ways. Communicate effectively. Present, assess and analyze appropriate supporting data/ evidence.	Evaluate systems models for how closely they represent reality. Conduct experiments to determine whether a hypothesized change creates the desired outcomes. Assess the nature of interdependencies in the system.

There are metacognitive strategies that make critical thinking development likely, but in the end they require context and deep learning and practice of domain knowledge [91]. An appropriate balance among types of knowledge developed must be maintained. This suggests not fully delegating the teaching of functioning knowledge to capstone or design classes but embedding it in a variety of ways across a range of classes as suggested in the examples above. Deeper understanding of development in thinking skills and the intersection with declarative and procedural knowledge development is needed. Ultimately, "true expertise, or adaptive expertise is characterized by an ability to draw on knowledge to invent or adapt strategies for solving unique or novel problems within a knowledge domain – not just the blunt-force application of algorithms, no matter how adept the 'expert' is at their application" [3]. Flipped-classroom pedagogy has to thoughtfully align tasks and assignments with desired learning outcomes [92] and must include not only content-focused learning outcomes but problem framing and solving learning outcomes as well. As more ambiguity is introduced in flipped-classroom environments, more attention must also be paid to emotional aspects of learning [93] and to different personalities [94].

We have excluded discussion of project-based learning here, but there is an implicit assumption that learning about problem framing and solving requires development of individual capabilities, but must also be embedded in project-based classes. Non-routine problem framing and solving work nearly always requires a team of diverse perspectives and heuristics [13, 27]. However, simply handing students a project will not automatically cause them to develop and learn needed skills for framing and solving problems. These skills must be explicitly articulated and taught. The connection between teaching problem framing and solving skills and teaching teaming skills is left for exploration elsewhere [95].

4. Conclusions

Little explicit attention is paid to the development of underlying problem framing and solving capabilities in engineering classes, particularly outside design and new product development classes. This paper uses a framework grounded in learning theory to examine the fundamental capabilities that engineering students must learn to become effective at framing and solving problems: observe and notice; frame and reframe; imagine and design; and make and experiment. It uses the learning framework to explore approaches from critical, design and systems thinking, raising the possibility of synthesizing approaches to provide engineering students more comprehensive learning about how to frame and solve problems.

Development of problem framing and solving skills is as important as content learning and should be scaffolded over a degree program so skills are built and practiced throughout. This exploration aimed to provide a platform for further conversation about how engineering students learn to frame and solve problems. Ultimately, the goal is to discover and understand the variety of ways that engineering students are taught to frame and solve problems and articulate associated learning outcomes and teaching approaches to make them more explicit to both faculty and students. Preparing engineers to become meaningful contributors to the design of the future in which we will live and work requires more than design thinking; it requires students be facile in framing and solving a wide range of problems, drawing from as complete a toolkit as possible.

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