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Student Perspectives of the Nature and Purpose of "Deep Modeling" as Situated Knowing*

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Deep modeling is a practice of representing ideas in a way that is amenable to inquiry. In engineering, deep models often take the form of drawings or physical and digital prototypes. These models are created and used throughout a design process to discover, analyze, evaluate, and validate ideas about problems and possible solution approaches. This paper is an exploratory study into student perspectives about the nature and purpose of deep modeling. The study context is an interdisciplinary design sequence where students created a personalized Interdisciplinary Design Playbook as a means for documenting their evolving design knowledge. We pursued two questions through a situated knowing lens: (1) How do students describe the nature and purpose of deep modeling as a design practice – what is it, why is it important, when is it useful, and how to do it? and (2) What associations do students make across these dimensions of knowing that reveal conditionalized logics for how and why deep modeling is meaningfully employed? By taking a situated knowing perspective, analysis focused on the conditions under which students perceive deep modeling practices can be employed in meaningful and relevant ways. We present three cases of rich narratives and representations, illustrate similarities and differences across cases, and discuss findings. We conclude by speaking to the benefits of our approach for understanding student learning – moving from the behaviors we see students doing towards the meanings these behaviors hold for students.

Keywords: modeling; prototyping; informed designing; situated knowing; design playbook

1. Deep Modeling as a Design Practice: What, Why, When, and How

By their nature, design situations carry considerable uncertainty, complexity, and ambiguity [1–3]. To deal with this, designers draw on a variety of practices to iteratively build understanding and knowledge to inform design intentions, possibilities, and outcomes. One of these design practices is deep modeling [4]. In engineering design, deep modeling aligns with the practice of "prototyping".

What do we understand about the nature and purpose of deep modeling in engineering design? What is it as a design practice, why is it important or beneficial, when is it useful, and what are deep modeling methods or techniques? Deep modeling may be characterized as a practice of representing ideas in a "deep way" that is amenable to inquiry into what an idea achieves, how it works and may be used, and why it meets needs [4]. Deep models take the form of material or digital artifacts that embody critical elements of a design [5] such as physical prototypes, hand drawn sketches, computer-aided drawings, experience storyboards, and simulations [6].

Deep modeling is a necessary, useful, and high-performance design practice. It can support making knowledge-driven decisions, detecting positive and negative behaviors in a product's performance, and reflective practice [4]. As a knowledge-building strategy, deep modeling aligns with an innovation mindset of "fail early, fail often", where "(the) goal of prototyping isn't to finish. It is to learn about the strengths and weaknesses of the idea and to identify new directions that further prototypes might take" [7]. As an example, Gerber and Carroll [8] illustrates how low-fidelity prototyping allows reframing of failure as a learning opportunity and supports forward progress including confidence in creative design ability.

Deep modeling is a cognitive activity, a process of linking goals to outcomes [9] that supports material and visual thinking as well as collaborative design. As a cognitive activity, deep modeling is directed towards discovering, analyzing, evaluating, and validating ideas about problems and possible solution approaches [9, 10]. This includes eliciting details whose existence and relevance are unknown [11]. As artifacts, deep models serve as non-human cognitive agents that help build knowledge and understanding through active participation in the material and social world [12, 13]. They act as critical objects that embody technical knowledge and facilitate collaborative design during product development [13]. In this way, deep models work as boundary objects, or places of negotiation, in ways that can amplify inventive and collaborative problem solving [14], support interpretive flexibility and perspective taking, influence decision making [15], and integrate making with storytelling and enacting [16].

Deep models are purposeful; as tools to think with, inform decision making and forward progress

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	CONCEPTUAL MODELS	EXPERIENTIAL MODELS	FUNCTIONAL MODELS
HOW	Unrefined and quick prototypes and sketches	Quick yet interactive prototypes, sketches, storyboards, etc.	Refined and precise prototypes, simulations, pre-production models, or CAD drawings, etc.
WHY	Make ideas "real" in ways that externalize thinking while limiting early commitment to ideas	Explore the look and feel of an experience from the perspective of users	Reveal trade-offs, explore pros and cons, and test and troubleshoot performance
WHEN	Exploring early concepts to build understanding and knowledge	Refining early concepts via user research with potential for reframing	Evaluating, testing and validating solutions

Fig. 1. A continuum of when, how and why deep models are used in engineering design.

[10], and communicate and negotiate with others [13]. They come in many forms and exist along a spectrum of qualities from low to high fidelity and physical to digital spaces. They do not always need to be refined or functional. What matters is richness of detail and robustness so that models become sites for learning [17, 18]. As depicted in Fig. 1, the form and function of deep models runs a continuum from conceptual artifacts to experiential artifacts and functional artifacts [13, 19, 20] and illustrates how deep modeling techniques may be used throughout the design process, often iteratively [4, 5]. Differences in the purpose (WHY) and use (WHEN) of different techniques (HOW) indicates the ways deep modeling is a situated practice. In other words, the use of a deep modeling technique is rooted in situation-specific purposes.

1.1 Prior Work

Research on student perspectives of deep modeling often focus on prototyping. Deininger et al. [21] conducted a thorough study of novice designers' use of prototyping in engineering design across multiple dimensions of knowing. Findings were communicated as lists characterizing student perspectives on attributes of prototypes (e.g., what they are), how prototypes are used, when prototypes are used, and why prototypes are useful. Prototype attributes include a tangible model, a work in progress, a representation that doesn't maintain all properties, part of a complete design, and a three-dimensional object. Situations for when prototypes are useful include concept or idea generation, testing and evaluation, problem definition, user requirements, concept selection, and engineering analysis. Reasons why prototypes are useful include demonstrating or visualizing form and function, testing designs or proving a concept, identifying next steps, selecting a concept, communication, and iterating intentionally.

The authors also offer a list of prototyping best practices design teachers could encourage and discuss with their students [21]. Some list items express single dimensions such as why prototyping is useful: "The role of a prototype is to enable communication, inform decision making, and aid in learning. Prototypes can transcend all three roles at once." Other items seem to express associations across lists such as when and how prototypes are used to improve a design: "Prototypes are a tool, not just merely a stage in the design process. They should be used many times to improve the overall design, rather than a stage that you pass through just once." Another example suggests associations between how and why prototypes build knowledge that support iterative improvements: "Prototype failure can always be reframed as a learning opportunity. The failure should give insights into the next decision and iteration of the design." These kinds of associations illustrate the ways prototyping is a situated design practice, linking what students should understand about prototyping and how this can support purposeful prototyping activities.

Other studies compare engineering students to practitioners to identify key differences and explore progressions toward more expert-like behavior. One collection of studies on the role of prototyping in design [5, 13] compares mechanical engineering students' perceptions of prototypes to engineering professionals from many disciplines. They found that students in the study had a narrow perception of prototyping that emphasized building and testing functionality and feasibility of physical elements of a product; whereas professionals had a broad perception that included using prototypes as communication tools, as an aid in making decisions, and as a way to learn about unknowns throughout the process. Professionals also had a "loose definition" of prototyping as essentially anything that helps you make a decision, whereas students emphasized "specificity" in terms of constraining prototyping as particular kinds of prototypes (e.g., first design, full draft, device to test capabilities).

Another study offers a scholarship of integration framework that characterizes performance-based differences contrasting how beginning designers do design to how informed designers do design [4]. Informed designers are distinguished from beginning designers because they achieved a level of competency marked by a key shift towards becoming a design professional: a shift from rule or heuristic based knowing to situated knowing [22]. Within this framework, deep modeling represents one aspect of what it means to become an informed designer. Here, informed designers create deep models to learn about the situation and ways to approach it, reveal hidden assumptions, and limit early commitment to untested ideas. Informed designers make models "real" so they are amenable to inquiry into how and if they work. They do not assume an idea will work but rather build to learn in ways that reveal and test unstated assumptions. In comparison, beginning designers represent ideas at a surface level in ways that cannot be tested and commit early to untested ideas they assume will work, but likely won't. Other studies indicate that when students are asked to reflect on the benefits and uses of prototyping, they exhibit a shift towards more sophisticated descriptions [21] and towards broader process, team, and learning-oriented purposes [19].

1.2 Exploring Student Perspectives of Deep Modeling as Situated Knowing

An overarching goal in our research group is to characterize how students become designers – what they come to understand about design and how this informs their use of design practices. We are interested in tracing the arc of becoming a designer to better understand ways to support design learning. Some traces may focus on knowing *how* to approach a design situation (e.g., the actions a designer takes or the techniques employed), some on knowing *why* a technique should be employed (e.g., recognizing the nature of a design task and the benefits and risks for using particular techniques), and some on knowing *when* particular techniques are useful over the course of a design project. Collectively these traces represent a web of associations or conditionalized knowledge of knowing what to do under different circumstances.

This idea of conditionalized knowledge is foundational to how people learn. In particular, experts are distinguished from novices by having rich, structured, and conditionalized knowledge [23]. Experts gain breadth and depth of knowledge through experience and organize their knowledge in deep and principled ways that reflect conditions of use – situations of applicability and circumstances [24]. This enables flexible recall and adaptive use to new situations. One cognitive framework underlying these ideas is situative learning theory, a theory that characterizes how knowledge is generated through interactions and in relation to the context in which it is learned and used [25, 26]. From this perspective, learning cannot be separated from the context in which it occurs [27]. In this way, *situated knowing* involves recognizing and responding to a situation in relevant and meaningful ways: understanding not only the "how's" of what a practice entails but also the "why's" or conditions under which a practice is applicable and useful [28].

This situative perspective aligns with views of design as a way of knowing and doing [1], a way of knowing and reflecting in and on action [29], and as material and collaborative inquiry [12, 30]. By nature, design tasks are open-ended, goal-oriented, social, networked, complex and situated [2, 3], and research indicates these characteristics of design tasks introduce specificities in the corresponding cognitive activities that make up design practice [31]. As an example, because design situations are open-ended with multiple solutions, the practice of iteration becomes important to setting or framing the problem, testing and retesting ideas, and constraining exploration to converge on an appropriate solution [4]. From the perspective of becoming more expert-like, decades of research indicates that competent designers (those on a pathway towards becoming experts) work in qualitatively different ways than beginners. They are situation-focused, sensitized to the situational aspects of a design project [22].

For this exploratory study, we are interested in what students understand about the nature and purpose of deep modeling. By using a situated knowing lens, we can illuminate dimensions of knowing as student perceptions about the what, why, how, and when of deep modeling. We can also reveal traces of design knowing as indicated through the associations students make across these dimensions of knowing in ways that reveal their perspectives on the conditions under which deep modeling practices can be employed in meaningful and relevant ways. We pursue this goal through two interrelated questions:

- How do students describe the nature and purpose of deep modeling as a design practice – what is it, why is it important, when is it useful, and how to do it?
- What associations do student make across these dimensions of knowing that reveal conditionalized logics for how and why deep modeling is meaningfully employed?

We hope to contribute to the growing research on student perspectives on the nature and purpose of prototyping by expanding the field of view to the general practice of deep modeling, as a broader space on the use of modeling to support design inquiry. By referencing the informed design practice of deep modeling, we hope to provide depth of meaning to the kinds of design knowledge and behavior that can serve as relevant learning goals for students in capstone design experiences [4].

More importantly, by taking a novel situated perspective that aligns theories of learning and design knowing, we hope to reframe the ways we think about design competency to reflect not just "doing a technique well" but "knowing how to design under different conditions". In the following sections, we describe study methods, present three student cases, compare across cases, and discuss insights gained.

2. Methods

The study context is an interdisciplinary design sequence in an engineering program at a research-intensive university. The sequence includes an abbreviated five-week methodology session in the fall followed by a 16-week capstone session in the spring. The project focus was "cultivate safety" and students had access to a subject matter expert in consumer product safety and human-centered design. During the fall, students engaged as individuals in iterative design sprints: conducting need-finding and prior art research on safety hazards to build knowledge about opportunities to cultivate safety, synthesizing research to identify problem frames and generate solution ideas, and using a variety of deep modeling techniques to explore and learn from solution ideas. For the spring session, students worked in small teams to identify and validate an opportunity for cultivating safety, and to deliver and verify performance of a working prototype. Students had freedom regarding project focus, but were held accountable for justifying their choice with relevant research. Teams received scheduled feedback on team management, initial problem frames and solution options, preliminary designs, and final solution delivery. Teams were also encouraged to interact with subject matter experts and users.

2.1 Study Data: Interdisciplinary Design Playbooks

The data is from an individual assignment completed as a draft in the fall session and finalized in the spring. The Interdisciplinary Design Playbook assignment is a personalized summary of a student's interdisciplinary design knowledge. The goal is to support continual learning by helping students make their design knowledge explicit in ways that support deep learning and transfer to future situations. As shown in Fig. 2, Playbook content is based on nine informed designing practices [4] and six interdisciplinary thinking practices [32, 33]. For each practice, students were given instructions for articulating what the practice means, why it is beneficial or important, when it is useful over the course of a design project, techniques and methods, and connections to interdisciplinary thinking and prior experience (see Fig. 2). This scaffolding provides a mechanism for students to express their evolving perspectives of informed design practices along multiple dimensions of what-why-when-how as well as the associations they make linking particular actions (i.e., doing a technique) to particular conditions of use (i.e., know why or when a technique is useful) [32]. Individual assignments generated Playbook content and were shared with peers so students could benefit from seeing other perspectives including practices they struggled with understanding.

Students had freedom to design Playbooks in ways that accounted for their learning preferences and could enable future use. Personalized qualities included visual representations, worked examples, design process models, narratives of lessons learned, advice to a future self, and hyperlinked content. Playbooks ranged in length from 2-page brochures to 40-page word documents and 60-slide PowerPoint^{TM} slide decks. Students had multiple opportunities to update Playbook content and iterate towards a personally meaningful and useful Playbook design. Final Playbooks were graded using a rubric that emphasized personal growth: a personalized design (design choices are evident), demonstrates personal growth (e.g., lessons learned, shifts in thinking, advice to future

INTERDISCIPLINARY DESIGN PLAYBOOK CONTENT		
9 Informed Designing Practices	*6 Interdisciplinary Practices*	*Instructions*
Do research Problem framing Idea fluency **Deep modeling** Strategic iteration Reflective thinking Balance tradeoffs Valid experiments Diagnostic troubleshooting	Perspective taking Critical thinking Contextual thinking Systems thinking Integrative thinking "Design for X" integration	WHAT: define the practice in own words WHY: explain benefits of use / risks of not using WHEN: explain when practice is useful HOW: identify and share techniques or methods CONNECTIONS: interdisciplinary practices and prior experience

Fig. 2. Interdisciplinary Design Thinking Playbook content (Deep modeling emphasized in bold).

self), comprehensive and thorough coverage of all practices, well-organized for future use, and easy to understand. For this study, we analyzed the content of complete final Playbooks but with a focus on the practice of *deep modeling*. This allowed us to zoom in on students' understanding of deep modeling while remaining open to the ways deep modeling was associated with other practices.

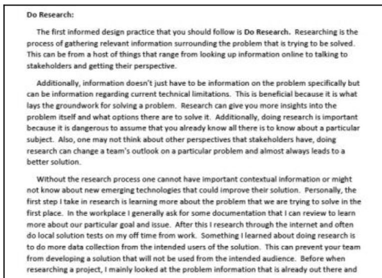
2.2 Study Participants

As an exploratory study, we purposively selected three cases for analysis. The larger dataset included 22 students from the 2019–2020 cohort and 24 students from the 2018–2019 cohort. Due to the COVID pandemic, the last 6 weeks for the 2019–2020 cohort moved from face-to-face instruction to virtual instruction. This impacted team interactions and the feasibility of fabricating working solutions. Cases were selected using three criteria: extensive evidence of Playbook updates, richness of description, and diversity of Playbook design. Collectively, these offer a strong start point for assessing the feasibility of analyzing Playbooks and analyzing the remaining data from a constant comparison approach [34]. Evidence of Playbook updates was used to ensure content incorporated lessons learned, shifts in perspective or new insights gained through the capstone experience. Richness of description was evidenced by reflectivity and depth of explanations and annotated work examples. Across the dataset, 10 cases clearly met criteria. While all students included text and visuals to articulate their perspective, the diversity of Playbook designs ran a continuum from high narrative (emphasis on text with some visuals) to hybrid (mix of text and visuals) to high visual (emphasis on visuals with some text). This continuum is illustrated in Fig. 3 for the three selected cases.

2.3 Analysis

Our analysis framework is situated learning theory, which focuses analysis on how students characterize dimensions of deep modeling (i.e., what, why, when, how) as well as the associations students make between doing design (i.e., how) and knowing conditions of use (i.e., what, why, when). We used an inductive qualitative research approach that prioritizes the student perspective and being open to unanticipated perspectives. More specifically, we used the constant comparison technique [34-36] to systematically make comparisons of similarities and differences across cases. This supports breadth and depth in characterizing student perspectives of deep modeling.

Because the authors are theoretically and personally sensitized, we discussed our positionalities prior to engaging with the data. The first author is the instructor for the two-term design sequence and sees design learning as helping students conditionalize or situate their design knowledge. She is also a co-author of the informed design framework that grounds the Playbook assignment [4]. As an instructor and researcher, she may be blind to alternative perspectives or jump too soon to data reduction or interpretation. Working with the second author, who is not familiar with the students or assignment, provided an important mechanism for being inclusive and critically reflective of research assertions. The second author is a doctoral student in engineering education and a full-time instructor supporting a design sequence in bioengineering. He is new to qualitative research but has considerable experience with students' use and understanding of deep models, particularly for human-centered and multidisciplinary projects. Through experience he has come to understand deep modeling as a critical component of multidisciplinary collaboration and communication, a method to visualize and evaluate ideas throughout a design process, a means for identifying potential failures and getting feedback, and an iterative pathway towards increasing the value of a solution to stakeholders. He has observed how deep modeling is not always intuitive to students and that students struggle with creating effective deep models. Therefore, he was particularly interested in using this

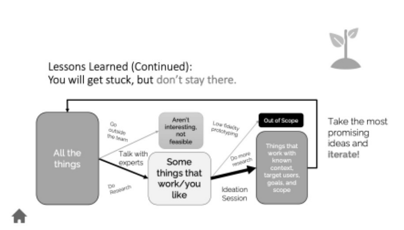


Do Research:

The first informed design practice that you should follow is Do Research. Researching is the process of gathering relevant information surrounding the problem that is trying to be solved. This can be from a host of things that range from looking up information online to talking to stakeholders and getting their perspective.

Additionally, information doesn't just have to be information on the problem specifically but can be information regarding current technical limitations. This is beneficial because it is what lays the groundwork for solving a problem. Research can give you more insights into the problem itself and what options there are to solve it. Additionally, doing research is important because it is dangerous to assume that you already know all there is to know about a particular subject. Also, one may not think about other perspectives that stakeholders have, doing research can change a team's outlook on a particular problem and almost always leads to a better solution.

Without the research process one cannot have important contextual information or might not know about new emerging technologies that could improve their solution. Personally, the first step I take in research is learning more about the problem that we are trying to solve in the first place. In the workplace I generally ask for some documentation that I can review to learn more about our particular goal and issue. After this I research through the internet and often do local solution tests on my off time from work. Something I learned about doing research is to do more data collection from the intended users of the solution. This can prevent your team from developing a solution that will not be used from the intended audience. Before when researching a project, I mainly looked at the problem information that is already out there and



HIGH NARRATIVE	HYBRID	HIGH VISUAL
Student B	Student A	Student E

Fig. 3. Variation in Playbook design and selection of 3 cases.

study to broaden his understanding of common student pain points and misunderstandings with an eye towards developing teaching insights for helping students learn and gain practical knowledge.

To account for different training and positionalities, the process for analyzing the data included training cycles to develop a shared understanding on what constitutes a reliable evidence trail and check points to critically reflect on how positionalities may influence what we notice and how we interpret observations. Although not included in this paper, we analyzed two additional cases to check the utility and inclusivity of exploratory findings and found similar perspectives. Overall, the analysis process was iterative with multiple passes to assess the quality and utility of assertions, and tease out similarities and differences among cases. To structure the process, we created a template to systematically analyze the data and used a web-based collaboration software, Miro^{TM} [37], to visually represent findings. Overall, data analysis focused on (1) linguistic cues (e.g., cues indicating shifts in perspective, explanations, experience-based insights, etc.), (2) repetitions as signifiers of prominent ideas, (3) similarities and differences within a case and across cases, and (4) associations (e.g., via linguistic cues such as if/then explanations, conditions of use statements, rationales or consequences, etc.). After analyzing cases, we reorganized insights into representational forms to create big picture views of student perspectives on the nature and purpose of deep modeling. To discuss findings, we engaged with existing literature to identify complementary findings and ways our analysis offered new framings or insights.

3. Student Perspectives of the Nature and Purpose of Deep Modeling

The following sections present three cases of students articulating their perspectives of deep modeling as situated knowing. Because Playbook content was generated through individual assignments referencing many experiences, only a brief description of the spring capstone project is provided.

3.1 Student A: Hybrid Playbook Design

Student A was in a 4-member team working on a battery powered high speed motorcycle for land-speed racing trials. The motorcycle was owned by a faculty member and has been used for other undergraduate and graduate design projects. His final Playbook was a 75-slide PowerPoint^{TM} deck. His Playbook is an example of a hybrid design (see Fig. 3) because most Playbook pages are formatted with text on the left side and complementary images on the right. Images are drawn from project artifacts, class discussions, and homework. His rationale for this design was that being able to capture the story of a project helps him reflect and see lessons learned.

Student A identified his final version of "deep modeling" as being notably different than his draft version. In his draft Playbook, Student A described deep modeling as: "making of a prototype that is focused more on the ideas at play than the form of the actual prototype. The importance of this is to make a prototype quickly that identifies key areas of concern. Techniques for this can be low fidelity models that allow the user to interact with the form and communicates key ideas. This can be done during the prototyping phase of a project, but iterations can be made at anytime . . . This can be done for interdisciplinary teams where backgrounds are different to better communicate design ideas that members of the team may not understand when only communicated orally." Qualities of how, why, when, and how are evident in this description, and many remain evident in his final Playbook. There were also changes and additions. He identified a shift in perspective of seeing a continuum of different deep model techniques that are useful based on different purposes over the course of a design project timeline. He also added new perspectives such as understanding deep modeling as both problem-focused and solution-focused, as graphical techniques to understand system relationships, as a means to support communication with users and among team members, and as a continual iterative process often co-occurring with other informed design practices.

Fig. 4 is a visual summary of Student A's views on the nature and purpose of deep modeling, and elements in the figure are drawn from the student's language and Playbook images. At the center of Fig. 4 is a gray arrow that signifies a project timeline and is populated by informed design practices (see Fig. 2). This timeline represents "when" Student A references deep modeling techniques in relation to other informed design practices throughout the design process. This arrow is not meant to represent a linear process; rather, solid black loops signify iterative cycles Student A identifies with deep modeling. Some iterative cycles are within deep modeling, some link deep modeling and idea fluency, and some link iterative deep modeling with balancing trade-offs, valid testing, and diagnostic troubleshooting. At the top of Fig. 4 are techniques for "how" Student A created deep models. These reference work artifacts such as graphical maps and system diagrams, concept maps, storyboards, sketches, CAD drawings, 3D models, and FEA analysis. The solid gray arrows denote associations between deep modeling techniques and other

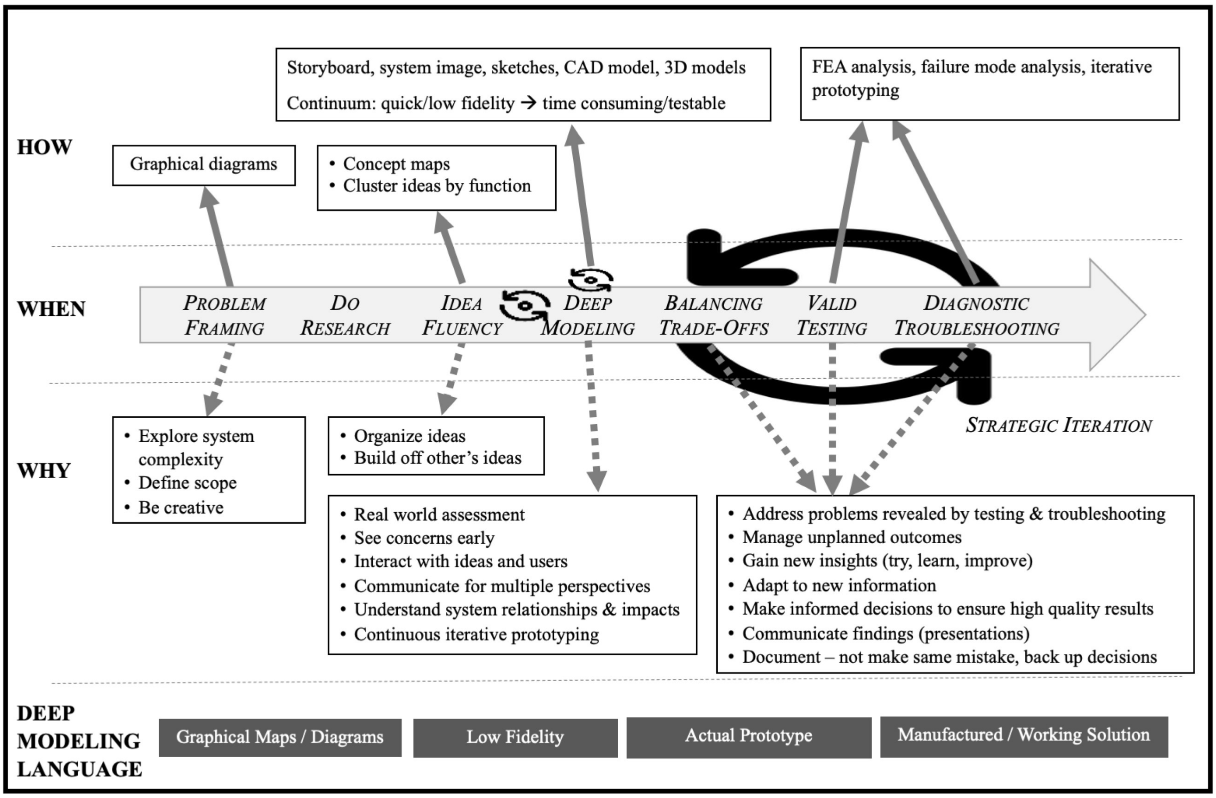


Fig. 4. A representation of Student A's perspective on the nature and purpose of deep modeling illustrating how, when, and why dimensions of knowledge as well as their associations.

informed design practices. The figure also depicts descriptions of deep modeling in terms of their purpose or "why" a technique is important or beneficial. As shown by the dashed gray arrows in Fig. 4, Student A identifies many reasons for using deep modeling (e.g., see concerns early, communicate, understand system relationships) as well as benefits associated with using deep modeling techniques to support other informed design practices (e.g., organizing information and ideas, examining the project context or broader system, building off other's ideas, and iterative prototyping). Collectively, Fig. 4 represents Student A's perspectives on the how, when, and why of deep modeling as well as the associations he makes among different practices and ways of knowing. Details of prominent associations are provided in the following sections.

3.1.1 Continuum of Purposeful Deep Modeling Techniques

Student A identifies many uses for deep modeling techniques, populating a continuum of different deep modeling techniques for different purposes or situations over the course of a design project. In other words, he distinguishes different deep modeling techniques (how) with different purposes (why) as a continually iterative process (when). In his final Playbook, he characterizes low fidelity models as "quick" in ways that can be made with simple materials to identify "key areas of concern" and as "focused more on ideas at play" in ways that allow "real world" assessment. He provides an example of a "low fidelity model of the chassis" that "allow(ed) the user to interact with the form and communicate ideas" and as being made of simple materials like 2×4 wood planks to "assess the real world ergonomics". He contrasted low fidelity techniques with techniques such as CAD models and 3D printed prototypes he describes as "time-consuming" but useful for "fitment checks", "customer presentations" and "other things down the process in the Diagnostic troubleshooting, analysis, etc." After hearing how other students in class suggested "don't make (models) too complex", he noted: "my mind was swayed. CAD and 3D printing are often too time consuming and there are better ways to get ideas across quickly". As a future lesson, he added: "it is important to recognize that CAD is not a tool to be used for ideation, but rather geometric iteration. It can sap creativity and takes too long to use for quick idea generation".

This continuum of purposeful deep modeling is also evident in the language Student A uses to refer to examples of deep models from his project. As shown on the bottom of Fig. 4, he associates graphical maps and diagrams with visualizing system inter-relationships as part of problem framing practices, low fidelity prototypes with ideation practices, actual prototypes with testing practices, and manufactured or working solutions with troubleshooting practices. This change in language complements how Student A describes the form and function of a deep model changing in relation to its purpose over a project timeline.

3.1.2 Supports Problem, Solution, and Communication-focused Practices

Another way of seeing a continuum of use for deep modeling techniques is the ways Student A describes deep modeling techniques as supporting other informed design practices (see Fig. 4): problem framing (e.g., graphical models to explore the problem from a systems perspective), idea fluency (e.g., create concept maps to organize ideas by function), balance trade-offs (e.g., use models to generate information to make informed decisions), valid testing (e.g., use models to run performance tests to reveal and respond to concerns), diagnostic troubleshooting (e.g., use models to reveal, document, and respond to failures), and strategic iteration (e.g., iterative prototyping to try, learn, and improve ideas). This indicates that Student A associates deep modeling with both problem-focused and solution-focused activities. Of particular interest is the ways deep modeling techniques help map, understand, explore, and monitor system complexity. From a problem-focused perspective, Student A explains how graphical representations help illustrate and justify project scope, and how system diagrams help "more clearly show the relationships" between contextual factors such as safety policies and regulations for isolated places with limited access to medical facilities. In other words, deep modeling techniques may be used to build knowledge about the problem from a systems perspective. From a solution-focused perspective, his team used deep modeling techniques to understand and monitor the inter-relationships among the different components of their solution. He explains how his team created a graphical "deep model (of) the entire system" to document and monitor solution interfaces: "Not only were ideas mapped out, but their interfaces and shared technical specifications were documented. This way, if anything was changed from the plan (which it was changed), the potential issues that would need to be addressed would be obvious."

Another prominent idea in Student A's Playbook was the value of deep models for enabling communication. Throughout his Playbook, he states how deep models manifested in visual forms are more useful than oral or text-based communication. For him, he personally appreciates "more graphical instead of bare text – I get lost looking at a document with just lists . . ." and how if he "could go back 1–2 weeks, I would encourage more . . . graphical instead of bare text". For interdisciplinary teams "where backgrounds are different", he explains how deep models "better communicate design ideas that members of the team may not understand when only communicating orally" and provide opportunities for team members to "build off each other's thoughts". For users, deep models help them to "interact with the form and communicate ideas".

3.1.3 Deep Modeling as a Continuously Iterative Process

A prominent topic in Student A's Playbook is the iterative nature of design. On the first page of his Playbook, he references a diagram from a course text [6] that depicts the design process as non-linear and iterative. Student A specifically describes deep modeling as an iterative process where "iterations can be made at any time" (see Fig. 4). From his perspective, sometimes iterations can be planned such as a "reoccurring stop and revelation point", and sometimes the inherent uncertainties of design projects require adapting to new requirements, insights or concerns. He explains, "(t)here is only so much that can be planned for, and strategic iteration takes into account the fast pace nature of prototyping." As examples, he notes how iterations can occur during "troubleshooting when problems arise" or after tests "deeming that your prototype is not successful at meeting the requirement". Iterations can also be problem-focused to reveal new insights and act on those insights to imagine new prototypes: "you could go back to the observations where you reflect and decide to conduct new interviews and questions that were missed before. . .new prototype iteration is then based on the insights gained." Student A explains the importance of iterative deep modeling as the benefits of looking for problems and concerns, being aware that unplanned outcomes can occur, and using iteration as a strategy of "try, learn, and improve" (see dashed gray arrows in Fig. 4). Overall, Student A associates iteration with high quality results: "Strategic iteration is the practice of using informed decisions to make changes to a design as new information is received. This is important as in order to have high quality results, the prototype needs to adapt to new requirements as they arise."

3.2 Student B: High Narrative Playbook Design

Student B was part of a 5-member team working on a load-reducing floating backpack to minimize the short and long-term damage of carrying heavy items. His Playbook was a 46-page Word™ document and it is an example of a high narrative design (see Fig. 3) because pages are predominantly text with a few representative images such as a cartoon, analogy, or process diagram. Images were typically externally sourced and not project artifacts. His rationale for this design includes the value of in-depth explanations, drawing from real world examples such as the course project and other experiences, reflecting on lessons learned, and articulating advice for the future.

In his draft Playbook, Student B describes deep modeling as ''more detailed and 'deep' explanations and/or representations of an intended design. These models can be inspected more closely to reveal strengths and weaknesses of the design when compared to shallow models. These are generally created after you have designed your initial shallow models in the idea fluency steps.'' Many of these ideas are evident in his final Playbook, including this distinction between ''shallow models'' and ''deep models''. For Student B, shallow models are initial ideas generated ''in the idea fluency step'' whereas deep models are detailed representations that can be ''inspected more closely''. Fig. 5 is a visual summary of Student B's views on the nature and purpose of deep modeling. Similar to Fig. 4, the center includes a gray arrow signifying a project timeline (when) populated by informed design practices, light gray arrows pointing to deep modeling techniques (how), and dashed gray arrows pointing to the benefits, need, or importance of deep modeling (why). As a collection, the figure represents Student B's views on the how, when, and why of deep modeling as well as the associations he makes among these ways of knowing and the ways deep modeling supports other informed design practices.

In the following sections we continue revealing how-why-when associations for deep modeling with an emphasis on bringing in new perspectives such as understanding and acting on strengths and weaknesses, combining strengths into a ''best'' solution, systems thinking, communication for multiple perspectives, and uncertainty and complexity as drivers for iterative deep modeling. We also identify how Student B's perspective is similar to or distinct from Student A. For example, Student B sees CAD models as time-effective, cost-effective, and easy to modify as needed: ''I learned that I actually preferred making CAD models. . .you can make design changes on the fly. . .I believe it is a very time and cost-efficient tool to use to speed up the design process as well as increase its effectiveness. Iterations can be worked through in a time efficient manner''. In comparison, Student A sees

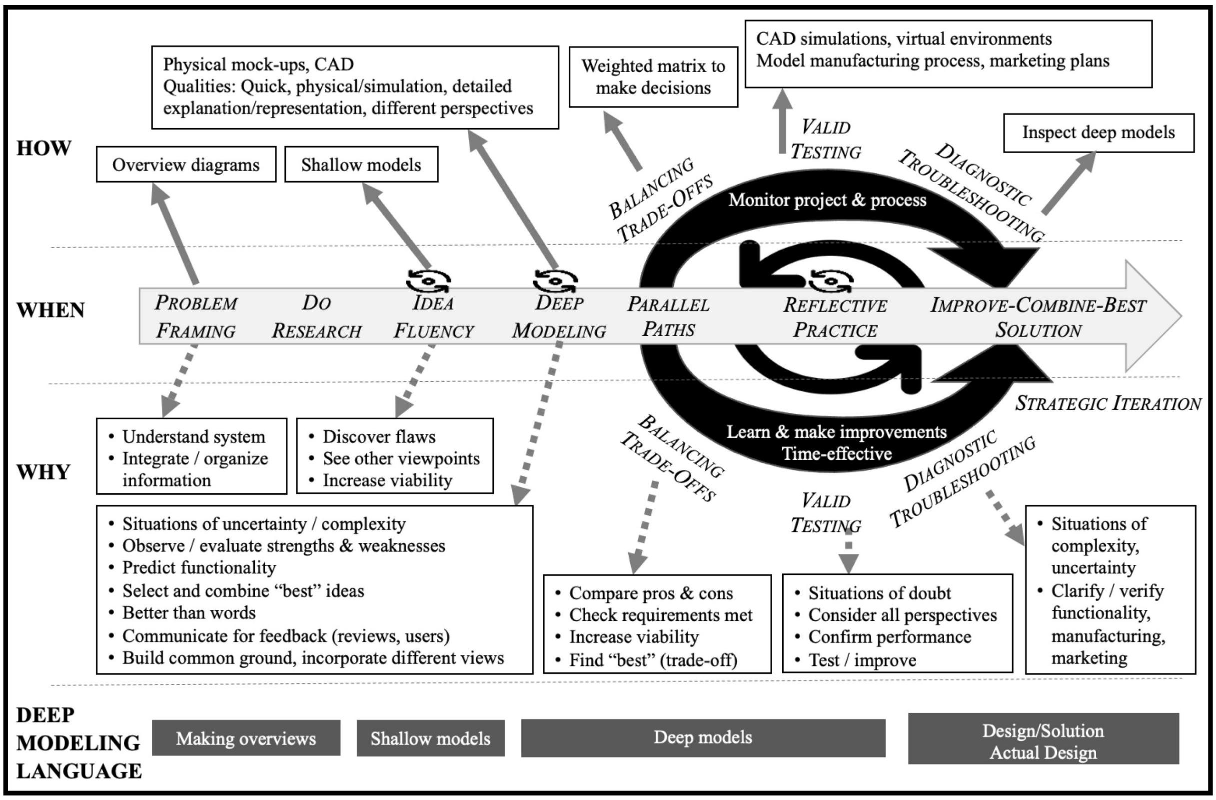


Fig. 5. A representation of Student B's perspective on the nature and purpose of deep modeling illustrating how, when, and why dimensions of knowledge as well as their associations.

CAD models as time-extensive, useful for geometric iteration but not for creative ideation.

3.2.1 Learn About and Act on Strengths and Weaknesses to Pursue "Best" Solution

Like Student A, Student B identifies a continuum of purposeful deep modeling techniques over time. A thread through these how-why-when associations is the way deep models can be inspected and critiqued to identify and act upon strengths and weaknesses. He explains that a key benefit of "detailed and 'deep'" models is their ability to "more closely reveal strengths and weaknesses . . . more accurately predict how the design will actually function" because the "strengths and weaknesses are . . . more prevalent" or observable. He warns, if "you don't do this you might end up with a design with unforeseen weaknesses". He further explains that revealing the strengths of solution ideas provides opportunities to integrate or combine strengths to produce the "best" solution. In this way, Student B associates deep modeling with integrative thinking: "incorporating other ideas with your own to produce better results" and using strengths "to cover areas in which there are weaknesses". He further explains that a risk of not having deep models is that you "might miss out on a design that had more strengths than you thought that either could have been chosen as a final design or you could have incorporated those strengths into another design".

3.2.2 Supports Problem, Solution, and Communication-focused Practices

Student B describes a variety of deep modeling techniques such as graphical diagrams, physical mock-ups, CAD drawings, and prototypes that can support testing and troubleshooting of feasibility, manufacturability, and marketability (see solid gray arrows in Fig. 5). These complement Student A (see Fig. 4); however, Student B includes a technique of making graphical models to assess, weigh, and balance trade-offs among different solution options. Like Student A, Student B's language for referring to deep models changes in relation to a particular purpose or phase. As shown in Fig. 5, organizing information and making visual overviews is associated with problem framing, shallow models with idea fluency, deep models for analyzing how an idea functions and performs, and the "actual prototype" or solution optimized through testing and troubleshooting.

The dashed gray arrows in Fig. 5 depict the ways Student B describes the benefits of deep modeling to support other practices. As an example of a problem-focused activity, Student B identifies constructing integrative system overviews as part of problem framing, "getting together relevant systems, patterns, and constructing overviews of an issue to be able to develop more adequate solutions". Similar to Student A, this is a systems thinking approach of weaving a "web of connections" that included "thinking about all of the different parts that might affect each other and how changing certain variables might affect other systems". His process for making these diagrams involves drawing out "micro systems and how they fit into a larger part of the whole system surrounding your problem" and creating "aspects of the system as bubbles and interconnect them with lines".

As an example of a solution-focused activity, Student B explains how and why coming up with many solution ideas generates "information to increase the viability of your solution to a problem" because "generating more ideas can lead to discovering flaws in prior ideas". For balancing trade-offs, evaluating the "positives and negatives of each design" involves having deep models so each idea can "be evaluated for all their strengths and weaknesses". For reflective practice, using deep models to observe strengths and weaknesses helps identify areas for improvement so for "the next iteration I try to either reinvent something to fill in the weak areas or I improve upon the design in areas that need it most". He connects this idea to a more general approach for continual improvement: "(it) is important because it allows us to improve upon our weaknesses. . .If you don't follow through with reflective practice you will stagnate the improvement of your design and yourself as a person."

Like Student A, Student B associates deep modeling with supporting effective communication by eliciting feedback, achieving common ground in the team, and incorporating different perspectives. A particular benefit of deep models is how they are "useful for those that are reviewing the design or giving feedback as it gives them a better idea of what the design actually entails and how it operates". Like Student A, Student B believes "a model or a CAD file is a more effective means of communication than pure words" because "words are limiting . . . as they can be interpreted differently by each person". A new perspective is that Student B sees deep modeling as helping a team get on the same page: "I truly believe that the deep modeling significantly contributed to the project as before this the entire team did not have the exact same idea in mind". He believes deep modeling made his team "more productive and stable". Another new perspective is how Student B sees deep modeling as a way to benefit from multiple perspectives. He explains that "Good models with a lot of complexity will incorporate different viewpoints . . . making sure that one understands other viewpoints on a given situation''. This allows ''everyone's voice to be heard'' and gaining information ''that you would not have thought of otherwise''. These ideas thread throughout his Playbook connecting deep modeling to problem framing, valid tests, diagnostic troubleshooting, and reflective thinking practices. For example, he suggests sharing deep models with manufacturers to help them ''get an idea of how the parts will need to be manufactured'', with mechanical engineers to ''get an idea an idea of how parts will interact and possible failure points'', and with marketing teams to ''get a better idea of what the intended use is and how they should market the product''. This can reveal blind spots since a ''mechanical engineer might believe a manufacturing assumption to be true whereas a materials engineer . . . (sees) this assumption is not an appropriate one to make''. As another example, he states that ''one has to incorporate (other perspectives) to develop a good problem frame. Many problems are not one dimensional and need to be looked at from many angles''.

3.2.3 Iterative Deep Modeling to Build Understanding and Manage Uncertainty

Finally, Student B characterizes two perspectives on iteration that are complementary but distinct from Student A. One perspective connects the inherent uncertainty and complexity of design situations to the need for iterative deep modeling; the other encourages a multiple paths approach to iterative prototyping as a way to learn about and combine the strengths of multiple ideas. Student B provides particularly rich explanations for why deep modeling techniques are beneficial, important, and necessary for situations of doubt, uncertainty, and complexity. He describes deep modeling as useful in ''complicated situations where there are many aspects to keep in mind and many possible solutions'' and ''where certain strengths and weaknesses of the design might be hard to evaluate''. For complex situations, ''where strengths and weaknesses are not well understood'' it can be difficult to compare options and assess trade-offs. In comparison with simple situations, ''it might only be necessary to come up with simple ideas as the complexity of the solution should be able to be understood without a model''. Therefore, a goal of deep modeling is to fill in the gaps of what is unknown and provide more certainty. Other benefits are provided in Fig. 5 (dashed gray arrows) such as (1) understanding the problem from a systems perspective, (2) observing, discovering, and evaluating strengths and weaknesses of ideas, and (3) enabling better communication than words to build understanding across different perspectives within the team and gain feedback from users and stakeholders.

Like Student A, Student B explicitly characterizes design as an iterative process. He identifies iterative cycles within idea fluency and deep modeling activities as well as parallel iterative solution paths. These parallel paths are denoted by a large iterative loop using deep models to compare pros and cons, balance trade-offs, test and improve performance, and ultimately combining the ''best'' elements of multiple idea paths. As shown in Fig. 6, Student B represents this idea as an existing design process diagram he modified to ''have several design paths going at once, take the good aspects of each path and combine them into one. . .final 'lane' of design that will be propelled forward through iterations and insights from other 'lanes'''. He called this a ''No stone unturned'' strategy.

While Fig. 6 is not located in the deep modeling section of his Playbook, it relies on the benefits of being able to evaluate and act on the strengths and weaknesses of deep models. For example, his iterative model relies on being able to evaluate and act on the ''strengths and weaknesses of designs to improve upon the next iteration''. He also connects this to his views on reflective thinking as a way to learn and apply what is learned to a future iteration: ''go through several design iterations and reflections. This allows one to learn and apply what they learned to their next iteration''. Finally, his process model includes iterating on the project goals –

Fig. 6. Modified iterative design process model used to articulate a personalized multi-lane iterative process model.

assessing if they are accurate and achievable as well as if goals are being met. Student B notes, "This is an area I need to improve upon . . . clearly defining the goals I want to accomplish with my solution. Then make sure that each iteration gets closer to those said goals. I have learned that keeping your goals the number one priority during the whole iteration process is very helpful".

3.3 Student E: High Visual Playbook Design

Student E was part of a 4-member team working on a personal safety device, *ProtectHer*, for college-aged women. Her Playbook was 114-slide PowerPoint^{TM} deck with a 44-slide Appendix (including class insights, previous assignments, and project artifacts). Her Playbook is an example of a high visual design (see Fig. 3) because visual information is prominent over text-based information where each slide is highly stylized, has hyperlinked text, and is populated with visual stories and project artifacts (e.g., schematics, diagrams, animations, simulations, prototypes, etc.). For her, visual cues help with quickly identifying important information, real examples support recall, and making connections between design, interdisciplinary thinking, and personal experience enables future use.

In her final Playbook, Student E defines deep modeling as a way of "representing an idea in a meaningful way. This can be done physically, digitally, theoretically, as long as the medium conveys key concepts . . ." In a "lessons learned" statement about her deep modeling experiences, she offers this advice (emphasis in bold from student): "it is best **not to be a perfectionist** with it. Although you and others may feel the need to keep making small changes to your design before really discussing and testing it with others, this will only **slow things down**. The best way to know if your design works or not, is **put it out there** in a way so others can interact with it and provide feedback. Like many aspects of the design process, it is a continual learning process of designing, testing, and re-designing. However, deep modeling is just **as much rewarding for the time it requires**." Fig. 7 is a visual summary of Student E's views on the nature and purpose of deep modeling. The center includes a gray arrow signifying a project timeline (when) populated by informed design practices, light gray arrows pointing to deep modeling techniques (how), and dashed gray arrows pointing to the benefits, need, or importance of deep modeling (why). As a collection, the figure represents Student E's views on the how, when, and why of deep modeling as well as the associations she makes among these ways of knowing.

In the following sections we continue to illuminate how-why-when associations for deep modeling

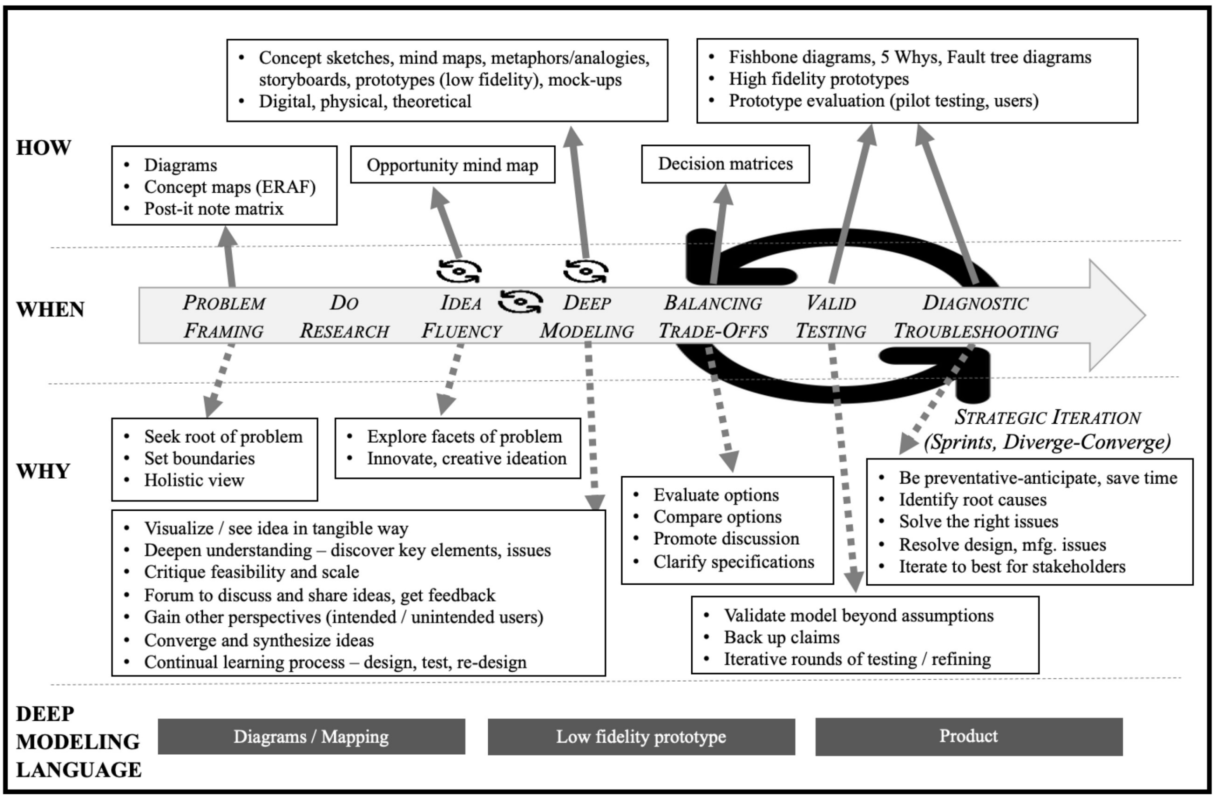


Fig. 7. A representation of Student E's perspective on the nature and purpose of deep modeling illustrating how, when, and why dimensions of knowledge as well as their associations.

with an emphasis on bringing in new perspectives such as the ways deep models create forums for meaningful discussion with users and support marketing analyses, and how and why deep modeling is an iterative learning process. We also continue to identify how student perspectives are similar or distinct. A comparison of the summary figures (see Fig. 4, 5, 7) shows that many of Student E's perspectives are resonant with the other students. For example, she describes deep modeling as existing on a continuum of purposeful use and associates deep modeling techniques with problem, solution, and communication focused activities. She offers similar reasons for why deep modeling is beneficial or necessary and expands on Student B's perspectives on communication and engagement with others to gain multiple perspectives. Similar to both students A and B, she perceives deep modeling as an iterative process and her language for referring to deep models changes over the course of the project from symbolic to more concrete forms (e.g., from diagrams/mapping to low fidelity prototype to product). There are differences, perhaps nuances would be a more appropriate term. For example, she is more explicit regarding engagement with users and stakeholders, and she offers a different viewpoint on what makes a deep model "deep".

3.3.1 Meaningful Representations that enable a Forum for Discussion, Critique, and Iteration

As shown in Fig. 7, Student E describes a variety of deep modeling techniques such as opportunity mind maps, metaphors and analogies to existing ideas, storyboards of use, conceptual sketches, and low fidelity prototypes and mock-ups. Like the others, she describes these in ways that indicate a continuum of deep modeling techniques situated in particular purposes and phases of the process (e.g., the dashed arrows in Fig. 7). Unlike Student A or B, she doesn't go into detail about how different types of deep models are quick versus time-consuming or shallow versus deep. Rather, she unpacks her perspective on what makes any model "deep" and why deep models serve as meaningful and tangible cognitive tools for collaborative learning. She highlights these ideas in her Playbook with **bold** and underlined text.

For Student E, the practice of deep modeling involves "**representing an idea in a meaningful way** . . . as long as the medium conveys key concepts surrounding the thing designed". She describes the purpose of deep modeling as helping to visualize an idea in a "tangible way" that "gives others the **chance to actually see your idea**, which leads to deeper understanding and critic (critique) of the design". She explains how these are visually engaging communication tools that create "a forum" to discuss ideas, "allowing others to **offer a new perspective** to the modeled design could bring to your attention potential opportunities and challenges that you otherwise wouldn't have seen alone". These other perspectives include intended and unintended users who help with "pushing the design to improve and becoming a more complete solution to the need trying to be filled." Within the team, she states how deep models "play a crucial role in synthesis" as a means for "converging ideas when exploring concepts". Overall, she describes the goal of deep modeling as "continual learning" through a process of discovery, synthesis and iterative "designing, testing, re-designing".

3.3.2 Supports Problem, Solution, and Communication-focused Practices

Student E also sees deep modeling techniques as supporting other practices – prior to ideating such as during problem framing, in combination with idea fluency, and after creating deep models of solution ideas as part of balancing trade-offs, valid tests, and diagnostic troubleshooting. As shown in Fig. 7, she references diagramming, concept maps, and Post-it^{TM} note matrices as ways to holistically visualize and organize information about the problem, to "develop constraints and boundaries", and iteratively "promote deeper digging" into the roots of a problem. Like Student A, she sees deep modeling as a means to conceptualize the problem and bound project scope, and like Student B she explains how graphical maps help to discover the root or "right problem". For idea fluency, she describes opportunity mind maps [6] as a way to support creative ideation while also helping explore different facets of a problem. This new perspective resonates with the practice of co-evolution often associated with creative experts [2, 3].

Student E's solution-focused associations stress the ways deep modeling facilitates producing the "best product for stakeholders". Many of these perspectives emphasize visual analysis techniques. Like Student B, she describes the use of decision matrices for comparing multiple deep models and "making a choice . . . (based on) assessing what is important". She also associates diagnostic troubleshooting with deep modeling through fishbone and fault tree diagrams as a means for anticipating potential failures or determining the root cause of an undesirable outcome. A new perspective she offers is the use of visual benchmarking analysis to review prior art and help the team distinguish their product "against solutions globally". Like the other students, she describes the use of "high fidelity prototypes in the final half of the design process" as a means to "validate model beyond initial assumptions".

Student E also makes many connections about how and why deep modeling facilitates effective communication and collaboration. For example, she describes how problem framing diagrams help "establish team understanding" and how sharing deep models of solutions helps "further develop the idea". She explains that deep models are "easy to share with others for feedback", create a "forum to share and discuss your ideas with others", and elicit "key insights from intended and unintended users".

3.3.3 Iterative Deep Modeling as a Learning Process for Making Informed Improvements

Similar to Student B, Student E provides visual narratives to illustrate deep modeling as an iterative learning process; one is a process of learning about the strengths of ideas to continually make informed improvements and the other is a divergent-convergent process of learning through trying out many ideas in ways that build problem-solution alignment. These visual stories are shown in Fig. 8. The top image represents a story of iteration grounded in project artifacts. It depicts an iterative process moving from insights gained through testing prototypes to making improvements so that "each iteration incorporates the best features from its preceding versions". She describes this as a process of "designing, getting feedback, and redesigning" that involved "let(ting) go of ideas if they are proven wrong or not useful". Elsewhere in her Playbook she shares how her team shared models to get feedback from users and experts such as police officers that offer safety training and campus police knowledgeable of a particular college context. These user-centered approaches are a prominent and distinct feature of Student E's perspective.

The bottom image of Fig. 8 depicts a personal reflection about deep modeling as an iterative divergent-convergent process and includes advice for her future self: "Take the most promising ideas and **iterate**!" The divergent process begins with taking in all ideas, doing research on these ideas such as talking with experts and users, and then converging on a subset of ideas that seem feasible or useful within the context or in reference to users.

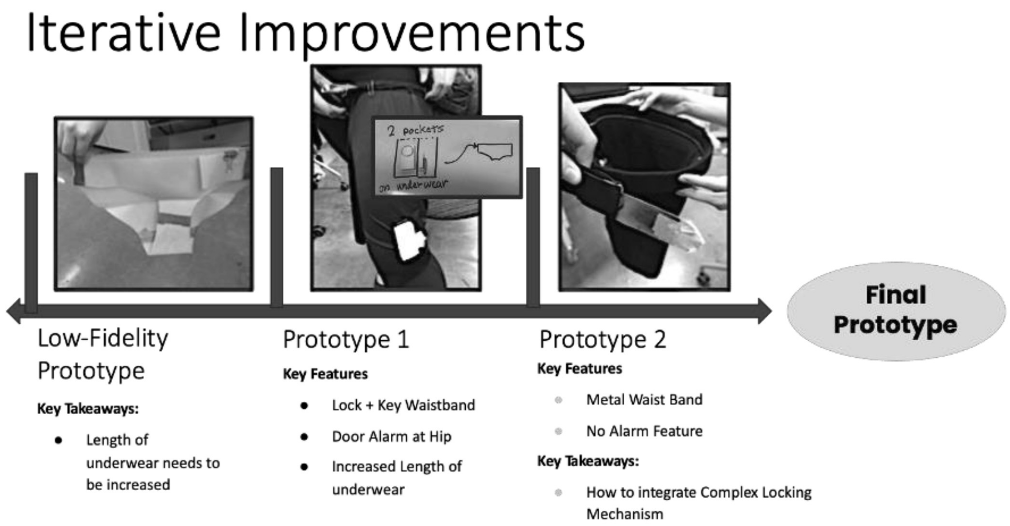


Fig. 8(a). Top: Low to high fidelity prototypes shaping iterative improvements.

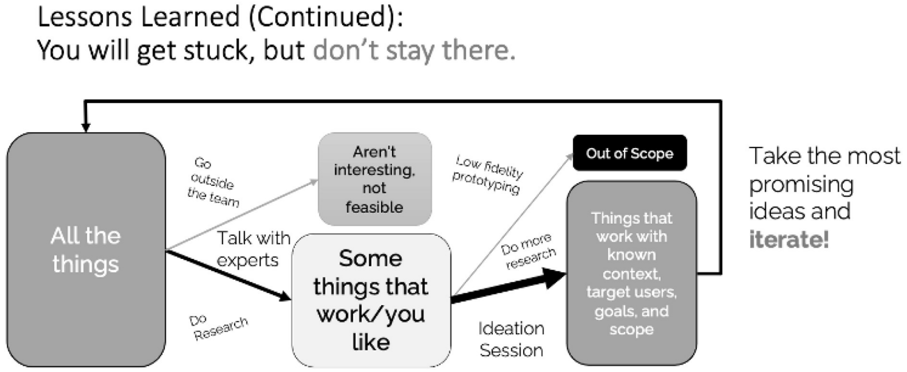


Fig. 8(b). Bottom: A divergent-convergent iterative learning process.

The narrative that complements this diagram explains how this process helps clarify project scope in ways that direct another ideation session. This process continues, taking "the most promising ideas and iterate" to "produce the best product for our stakeholders". This representation also resonates with one of the lessons Student E shares about her deep modeling experience: "The best way to know if your design works or not, is **put it out there** in a way so others can interact with it and provide feedback."

4. Discussion and Next Steps

We began this exploratory study with two questions: (1) How do students describe the nature and purpose of deep modeling as a design practice – what is it, why is it important, when is it useful, and how to do it? and (2) What associations do students make across these dimensions of knowing that reveal conditionalized logics for how and why deep modeling is meaningfully employed? We pursued these questions by analyzing Interdisciplinary Design Playbooks, an assignment that scaffolds reflection on the what, why, when, and how of deep modeling (see Fig. 2). We selected three Playbooks as variants of narrative and visual data (see Fig. 3) and observed notable differences in communication. For the high narrative Playbook (Student B), each practice was detailed with reflections that went beyond descriptions of experiences to deep insights gained through experience including lessons learned. Images were also synergistic with the narrative and provided an alternative way to communicate ideas. For the high visual Playbook (Student E), images served as tangible work artifacts to explain ideas and as abstraction devices to pull out lessons learned and future advice. For the hybrid Playbook (Student A), some images lacked explanation or synergy with the narrative and were not included in the analysis.

We created summary representations (see Fig. 4, 5, 7) and identified similarities and differences. Student perspectives were remarkably similar even though projects were quite different. These differences were nuanced. Many differences seem synergistic such as characterizing different but complementary characteristics of deep modeling as an iterative practice. There was only one disagreement, between the ways Student A and B characterized attributes of CAD drawings (e.g., too time-intensive for quick learning versus time-efficient for analysis and feedback). It's not clear if either view should be judged as inappropriate or problematic; difference could be attributed to personal capabilities or dispositions toward CAD that supports time-effective uses.

4.1 Nature and Purpose of Deep Modeling: Knowledge of Why, When, and How

The summary representations offer an inclusive collection of student perspectives about why, when, and how deep modeling practices can be employed in meaningful and relevant ways (see Fig. 4, 5, 7). Focusing on "why" reveals student perspectives about *conditions for use* (the nature of the situations that make deep modeling necessary) and *benefits of use* (the outcome gained). Two students identified situations of doubt, uncertainty, and complexity as driving the conditions for using deep modeling – explicitly (Student B) and as part of an iterative prototyping strategy (Student A). Regarding benefits of use, students described deep models as capturing important information in ways that enable inquiry and learning: as tangible representations of an idea that convey meaningful information and create a forum for discussion (Student E), as embodying details that can be inspected for strengths and weaknesses (Student B), and allowing discovery of concerns or flaws through real world assessment (Student A). Students perceive deep modeling as purposeful, directed towards goals such as integrating and organizing large quantities of information, setting project scope, seeking the root of a problem, gaining a holistic view, innovating, building off each other's ideas, seeing concerns or flaws early, making comparisons and informed decisions, testing and validating performance, monitoring system interfaces, anticipating failures, and iterative improvement. Many of these benefits resonate with prior work such as understanding the problem, gathering feedback, evaluating and testing ideas, selecting concepts, communicating, collaborating, and identifying next steps [21]. An unexpected finding is that the students in the study have a broad perspective on the role of prototyping in design similar to professionals – as an aid in decision making, as communication tools, a way to learn about unknowns throughout the process, and as transcending all three roles at the same time [10].

Focusing on "when" reveals the ways students see deep modeling techniques as useful *over a design process* as compared to only a phase. For example, Student A initially viewed deep modeling as part of the "prototyping phase" and shifted to seeing a continuum of purposes over the course of a project depending on circumstances and needs. All students associate deep modeling with iteration: as iterative prototyping, multi-phase iterative cycles to understand pathways towards a "best" solution, and planned or unplanned iterations. These align with best practices about what teachers should encourage with their students. For example, "Prototypes are a tool, not just merely a stage in the design process. They should be used many times to improve the overall design, rather than a stage that you pass through just once" [21]. Focusing on "how" reveals many *techniques* for modeling ideas in a deep way. Students identified a breadth of techniques covering many mediums for many purposes, that also align with perspectives teachers should encourage with their students [21]. One difference from prior work is that students included visual graphical techniques such as concept maps for problem framing, decision matrices for making informed decisions, fishbone diagrams to troubleshoot potential failures, and benchmarking matrices for assessing market viability. This may suggest our focus on "deep modeling" instead of "prototyping" encouraged students to identify a broader space of techniques that are comparable with how professionals see prototyping as "anything that helps you make a decision" [10].

4.2 Conditionalized Logics for Meaningful Use

The summary representations also illustrate conditionalized logics or situated ways of knowing deep modeling as manifested through why-when-how connections. We observed three logics: deep modeling as a *purposeful continuum*, deep modeling as *supporting other practices* (problem-focused, solution-focused, communication-focused), and deep modeling as an *iterative learning process*.

All three students expressed deep modeling as a continuum of techniques with distinct benefits or purposes. Two students named their continuum variations such as low versus high fidelity or quick versus time-consuming (Student A) and shallow versus deep models (Student B). Similar to existing work (see Fig. 1), all students used different words to reference deep models over the course of a design project [13, 19, 20], signifying how the nature and purpose of deep models changes over time. Two students expressed themes underlying their continuums. Student B stressed deep modeling as a way to continually understand and act on strengths and weaknesses throughout the design process, and Student E stressed deep modeling as a forum for discussion and continual iterative learning. Overall, student perspectives correspond with messages teachers could promote about the purpose and nature of prototyping [10, 21].

Some situated logics reveal how students see deep modeling techniques as supporting other practices – as tools that have broad use versus just a stage in the process [21]. Similar to existing research, we anticipated and observed deep modeling as solution-focused inquiry such as making comparisons and decisions among options, being proactive in identifying concerns or failure points, and testing and verifying performance [10, 13]. Two findings not represented in prior work were classifying weighted decision-making matrices and system interface diagrams as deep modeling techniques. Another unexpected finding was how students associate deep modeling with problem-focused inquiry, identifying many visual diagramming techniques for understanding problems in holistic, contextual, and interconnected ways. This is comparable to how professionals perceive the role of prototyping in defining problems, project scope, and user requirements [21]. Students also associated deep modeling with supporting communication [13, 21], both within the team and with users and stakeholders, in ways that are "better than words" and enable feedback from multiple perspectives.

Finally, all students had rich narratives about deep modeling as an iterative process in itself (e.g., iterative prototyping) and as playing a role in iterations that build understanding about the problem and improve solution and team performance. The details of each perspective were nuanced but seem synergistic: continuous "try, learn, improve" iterations (Student A), "no stone unturned" multiple path iteration strategy (Student B), and a divergent-convergent iterative learning process for taking into account multiple perspectives (Student E). Iteration was also described as a way to overcome and manage uncertainty and complexity – a way of being proactive to anticipate failures as well as adapting to unplanned events. Students also stressed how their insights about iteration became lessons learned about deep modeling and design overall. Their advice for the future resonates with best practice: "Prototype failure can always be reframed as a learning opportunity. The failure should give insights into the next decision and iteration of the design" [21].

4.3 Benefits of our Approach and Next Steps

Although this is an exploratory study, we see three important contributions. First, by anchoring the study in the informed design practice of deep modeling, we provided depth of meaning to the kinds of design knowledge and behavior that can serve as relevant learning goals for students in immersive design experiences [4]. Perhaps because of this choice, we found that many study findings resonate with best practices instructors can convey to their students [21] and with more comprehensive understandings of prototyping similar to engineering professionals [10, 13]. Second, by focusing on this more general practice of deep modeling as compared to prototyping we were able to populate a broader landscape of purposeful inquiry techniques for building knowledge about design problems, solutions, and processes. Techniques covered an inclusive space from visual to material and virtual artifacts to support material and social inquiry [12]. An implication is that "deep modeling" might be a more productive instructional message than "prototyping". Finally, this study clearly shows that students have logics about their design approaches – logics that can be understood as situated knowing about what to do when, why, and how. By grounding the study in a situated knowing perspective, we revealed student's understanding of not only the "how's" of what a practice entails but also the "why's" or conditions under which a practice is applicable and useful [28]. Some logics are associated with understanding the core nature of design situations, such as ambiguity, uncertainty, and complexity [1–3] that drive a need for deep modeling; some are driven by the benefits or outcomes desired. As such, our approach offers a new framing of design competency that speaks to how designers come to understand good design practice through their experiences and how that shapes their approaches to design situations. This expands a learning goal from *knowing how to do a technique well* to *knowing how to design under different conditions* – moving from behaviors we hope to observe in our students towards the meanings these behaviors hold for our students as they become designers.

While this study is limited in scope, our analysis of three cases revealed rich and provocative student perspectives about the nature and purpose of deep modeling, most of which were shared although expressed in nuanced and personalized ways. We recognize the Playbook assignment likely served as an intervention in helping students learn through their experiences. This study is not an evaluation of this assignment, but findings indicate the benefits of having students reflect on and articulate their design knowledge in ways that support situated knowing. Findings also support the use of the Playbook assignment as a vehicle for exploring students situated knowing. Moving forward, we plan to analyze the remaining Playbooks as well as the other eight informed design practices.

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