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Engineering Design Representations: A Bestiary

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Engineering Design Representations: A Bestiary

Engineering design is inherently representational—designers use sketches, diagrams, schematics, storyboards, and other media to think through problems and communicate ideas. Research in design cognition and education highlights that external representations are not merely communicative tools but essential components of design reasoning. Yet undergraduate students often struggle with the meta-level understanding of when, why, and how to choose appropriate representations. To address this, we developed the *Engineering Design Monster Manual*, a visually rich, 50+ page supplemental resource that presents design concepts as illustrated "monsters," inspired by medieval and fantasy role-playing bestiaries.

Each "monster" personifies a different class of design representation—such as "The Block Diagram," "The Class Diagram," or "The Gantt Chart"—complete with illustrated traits, design context, strengths, and vulnerabilities. The manual uses humor, metaphor, and fantasy tropes to demystify technical representations and emphasize their roles across different design stages and their appropriateness for different audiences and contexts. It was developed iteratively with student feedback in a senior capstone course, refined through classroom use and reflection, and co-written using generative AI to save labor.

The manual supports a pedagogy where students build representational fluency alongside traditional design skills. Early evidence suggests that students learn over time and exposure engage with abstract design tools through repetition, iteration, and using representations as conversational artifacts. This paper describes the development process, pedagogical rationale, and alignment of the resources with theories of design learning and representational fluency. By drawing on elements of humor, narrative, analogy, and visual storytelling, the Monster Manual supplements design project development in capstone and other design courses.

Introduction and Goals

This paper reports on the development of an educational resource to support courses in engineering design. Several years ago the Electrical and Computer Engineering (ECE) Department at Bucknell University more than doubled the number of design courses to ensure students encountered at least one design course each year, avoiding a 'book end' curriculum [1]. As part of this curricular change [2], [3], [4], [5], which also reduced curricular complexity [6] by about 30% from 242 to 181, a 'design thread' was established in the curriculum. To date over 60% of the faculty in the department have taught at least one course in the design thread, with several faculty teaching across multiple courses. During the four years over which the curricular change was implemented, faculty met regularly to ensure there was a coherent progression, or thread, to the sequence of design courses.

To organize the design courses around a coherent theme, the participating faculty looked at several options including teaching one of many versions of the design process, adopting course models that focused on product design, entrepreneurship, or focusing on durable skills like communication and teamwork, but eventually chose design representations as the major organizing framework. The choice of design representations was to help abstract the design process while also supporting the skills that come with doing projects. Students still complete projects, but the focus is less on following a given process or focusing on the end product than using design representations to iteratively refine the design. Atman [7] has shown that expert designers shift frames in their design thinking more, and we sought to create opportunities for students to practice frame shifting.

As the 'design thread' increasingly focused on representation, faculty observed that durable or transferable skills like communication, teamwork, and socialization of engineers also improved. While there has historically been debate and tension around the extent to which, or even if, time spent developing such skills should be part of the engineering curriculum there is increasing evidence—both locally and more generally—that attaining durable skills is increasingly important [8]. Locally, the department hears consistently from our advisory board that "*we assume given the degree and GPA that a student's technical skills are sufficient; it is the personal relationships and ability to work in the organization that are important*". Such anecdotes are supported by studies examining the value of a college degree which find the comparatively high value of an engineering degree arises from graduates who are innovative and capable of non-routine tasks including social skills [9]. Additionally analyses of job advertisements find durable skills are more frequency sought after and many have a higher wage premium [10]. This can create confusion on what faculty should teach – while students need technical knowledge for engineering, technical skills are strong differentiators for a more narrow set of good jobs.

The perceived tension between domain-specific technical knowledge and skills and the set of social abilities that are required for technical expertise to be used effectively within organizations exists mainly in faculty practices, however. There is no reason that technical and durable skills cannot be taught simultaneously – one way this may be accomplished is teaching design through representations that integrate technical and durable skills. Here the term 'design representation' is defined as a sharable artifact that captures of some set of specific aspects of a designer's conception of the overall design task they are undertaking. A representation is not an element of a complete, orthonormal basis set in the design space. Rather representations can be messy, incomplete, contradictory, and/or redundant. The important point is that they allow shared understanding to be built among a design team and project stakeholders. In ongoing efforts at Bucknell University the authors have sought to organize design courses to emphasize representational fluency rather than design products or processes [11]. This paper reports primarily on one part of that larger effort, making an educational resource to assist students develop representational fluency.

Design Representations

This section broadly discusses design representations and their role in the courses at Bucknell in order to provide context for the *Engineering Design Monster Manual* resource discussed in this paper. The importance of representations in learning and their usefulness in design has long been recognized. Research shows that multiple external representations—such as diagrams, schematics, sketches, and models—enhance students' understanding by linking abstract concepts to concrete experiences. Studies have found that visual representations improve comprehension, especially for students with low prior knowledge, by facilitating conceptual mapping and inferencing processes [12]. Drawing activities in STEM not only support retention but also improve conceptual integration [13]. In mathematics representational fluency—the ability to express an idea or concept in multiple forms—correlates with better learning [14], [15]. More generally, being fluent on a task is characterized by speed and accuracy, the ability to perceive structural patterns, reduced cognitive load, adaptive flexibility, and metacognitive regulation. Fluency is developed through deliberate practice with feedback, intentional schema building, reflection, and spaced practice [16], [17]. In the context of undergraduate engineering design, representations serve both as tools for communication and as scaffolds for design thinking and are central to the reasoning processes that define engineering practice, particularly in artifact and system modeling [18]. Just as it is in mathematics, representational fluency is a strong predictor of conceptual understanding in design tasks [19]. However, students interpret and utilize sketches, CAD models, and textual documentation differently, so scaffolding representational interpretation and creation is an important consideration [20].

One of the issues in using representations to teach design is that the number of possible representations is extremely large. While there are commonly encountered engineering representations that are widely familiar—e.g. block diagrams or Gantt charts—since representations are forms of cultural knowledge they are embedded in and contingent upon team norms, organizational practices, and the project details [21]. Because representations can be specific to organizations and impact upon how effectively resources (including time) are used in the design process, they provide competitive advantages and thus serve as cultural capital within an organization. Representations, while often highly technical, also intersect the space of durable and transferrable skills since they are used in communication, managing human aspects of a project, defining cultural practices, and defining roles. Thus, design representations are less of a fixed body of knowledge and more a set of practices centered on cultural artifacts or boundary objects; this impacts on how they are taught. The approach taken at Bucknell is to develop students' representational fluency so they become more adept at using representations in day-to-day design work. To support representational fluency, students are introduced to a large set of possible representations across the courses in the design sequence as described in the next section.

Building Representational Fluency

This section describes the iterative process faculty used over multiple course iterations to better develop representational fluency. Students are introduced to representations in the design courses and then use them to communicate their choices throughout the design process. Student teams are given considerable autonomy on which representations to engage with and how to represent different design choices. We hypothesize providing student such autonomy supports enhanced ownership of their project and intrinsic motivation [22]. To encourage repetition, representations are revised and refined over multiple design check-ins with feedback provided to students. Initially representations were assigned as readings then discussed in class. However when representations were introduced sequentially it was difficult to get students habituated to weekly 'one-and-done' homework assignments to see representations as a lasting and integral part of their project. Faculty had to continually remind students that design representations are as much design project as was the product, and that much of the work of engineers is to produce documents of various forms which enable others to build designs to specification. After introduction of the resource described subsequently the course instructors changed tactics and provided a set of possible representations that students could choose from rather than introduce each representation in class.

Although Atman's work has shown expert designers make mental jumps between stages of design, since students are novice designers, representations were at first loosely categorized into eight separate perspectives of the overall process of design. These eight perspectives, or lenses, are shown in Figure 1.

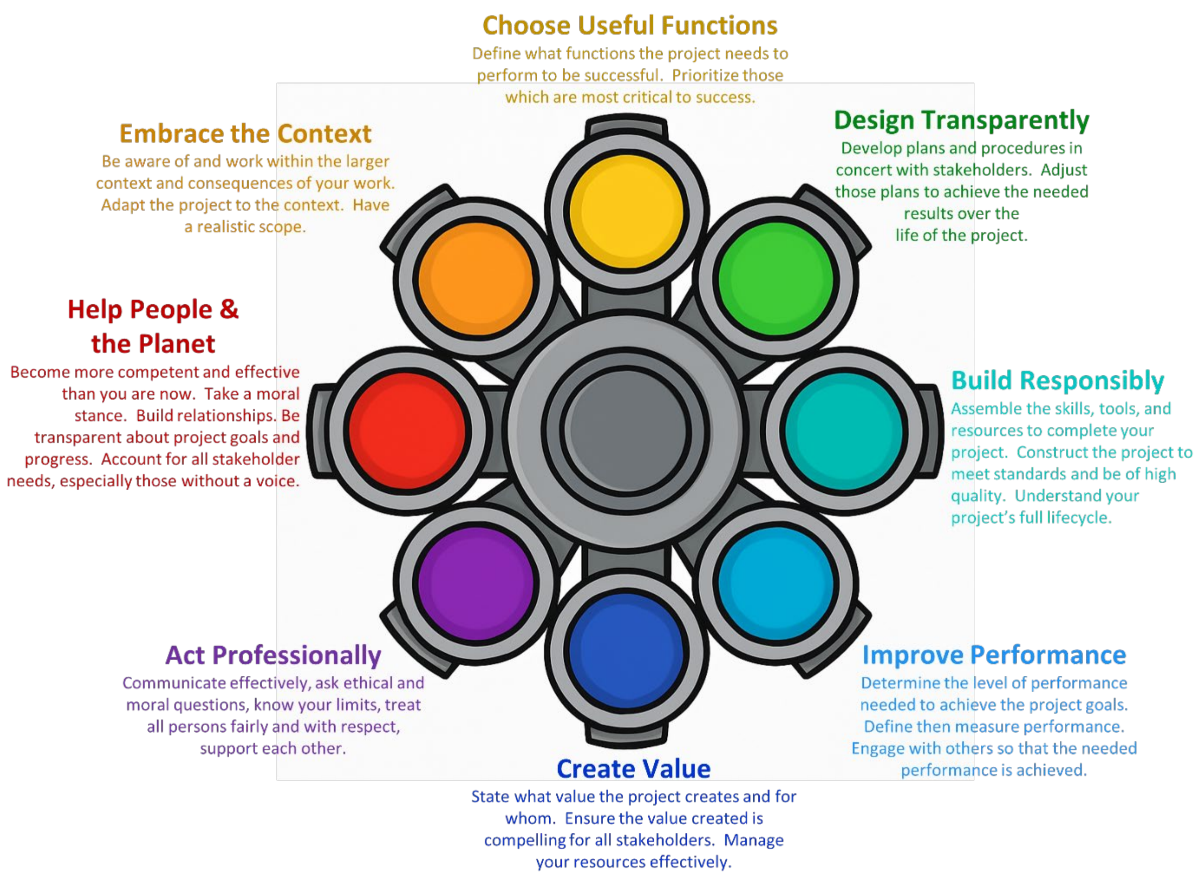


Figure 1: Eight separate lenses of design were used to loosely categorize representations to organize them around elements of the overall process of design.

The combination of giving students autonomy over selecting representations and sequentially introducing a large number of representations to initially choose from created a situation in which both students and faculty became overwhelmed. Faculty overwhelm came from having to support teaching materials and advise student teams on a one-by-one basis on how to select and best utilize representations. Student overwhelm came from choice overload on how to represent their design and the misunderstanding enforced in engineering science classes that there was some ‘right answer’ for choosing and developing representations that faculty weren’t telling them about. In other words, autonomy requires choice, choice creates uncertainty, and uncertainty requires support resources. The fact that representations are iterative and evolve over months or even a full academic year pointed to the need for better ways to present and organize design representations as part of the larger goal of supporting and developing representational fluency.

To organize and categorize representations, the authors first tried mapping them to the eight perspectives of the design process by modifying Figure 1 as shown in Figure 2; this turned out to be difficult to read and not particularly informative for students. While Figure 2 illustrates representations sorted on the dimension of task, there are many other dimensions on which representations can be classified – these are discussed subsequently. Another way to classify representations is through a set of tags supported by an ontology. An example is KEEN cards for entrepreneurial minded learning [23]. While tags allow highly flexible sorting and classification, the use of tags requires search tools and is not visually approachable or easily navigable by novices who are learning about representations.

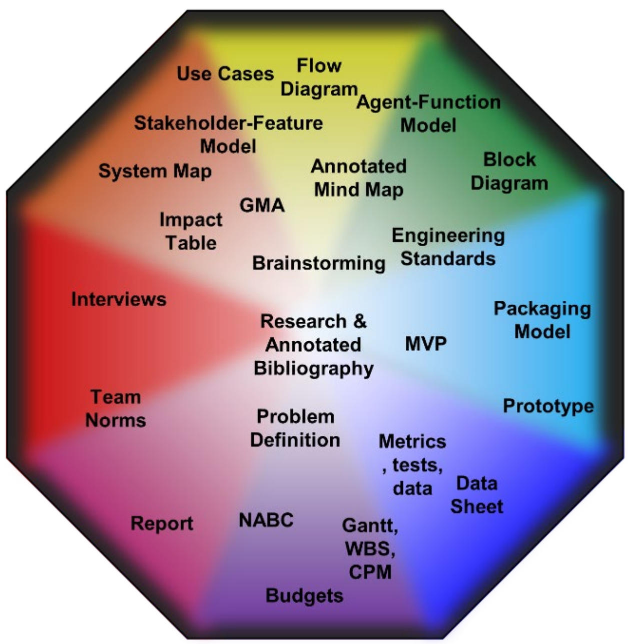


Figure 2: A first, ineffective attempt to characterize design representations by task using the eight different design perspectives – colors correspond to Figure 1.

To make representations both multi-dimensional and approachable, the authors drew on the literature and practices of games, particularly role-playing games [24], [25], [26], [27]. Unlike many board or card games, role playing games offer a high degree of freedom or agency to players in deciding actions [25], [26] since the rules are less constraining than in other forms of games. In role playing games players are confronted with an imaginary world they must navigate to achieve amorphous and evolving goals, similar to working in a design space. To create a coherent world, players' actions are constrained by a set of rules that determine the results of actions, similar to the role constraints play in design. One aspect of this rule set is to characterize creatures, items, and artifacts by a common set of traits that allow the results of actions to be determined. For example, in a fantasy role playing game a player in the game may wear armor that protects them from damage when they are attacked. The type of armor they wear determines things like the level of protection offered, how mobile they are, and how quickly they tire; e.g. someone in full plate and mail armor is better protected but moves more slowly than someone only wearing leather armor.

Building on the idea of a design project as an adventure, the authors made the analogy of representations as distinct 'creatures' which students would encounter during a design project, the same way adventurers encounter monsters. Drawing from examples of written guides to creatures in role playing games, our thought was that design representations could be characterized ontologically on multiple relevant dimensions. For example, one of classic texts in role playing games is the *Advanced Dungeons & Dragons Monster Manual* [28] which is a guide for players and game masters to creatures in the game. Based on medieval bestiaries (*bestiarium vocabulum*)—a popular medieval book cataloging real and mythical creatures that used each animal's traits as allegorical guides to spiritual truth—the *Monster Manual* provides a picture, short description, and table of common traits for each creature that players may encounter in a role-playing game. While a common set of traits—size, toughness, attack damage, etc.—is used to classify all creatures in the game the values assigned to those traits varies greatly depending on whether the creature is a dragon or a giant rat.

The Engineering Design Monster Manual
To briefly recap, design courses at Bucknell University seek to develop representational fluency in students as part of integrating technical and durable skills. Giving students' a choice of representations helped support intrinsic motivation [29], [30] and allowed for deliberative practice, but also created cognitive overload. To address this the authors developed an educational resource that catalogs a set of traits for each design representation used in the course as an organizational aid for schema building. Having a written guide summarizing the 'traits' of representations is intended to both introduce students to representations and guide them on how useful the representation would be for particular design goals, audiences, and tasks. This chain or reasoning led the authors to create an *Engineering Design Monster Manual* where each of the design representations students can use is represented as a 'monster' with a brief description that is classified on multiple factors.

In creating the resource a key goal was to provide a richer but self-consistent way of categorizing design representations beyond their usefulness in a given stage of the design process as shown in Figure 2 – 14 different ways to categorize representations were used which are listed in Table 1. After some deliberation, the authors chose a ten-point scale for the characteristics to provide quantitative comparisons by trait. The choice of the ten-point scale was arbitrary to allow sufficient discrimination between different representations without being overly complex. Both numerical values and textual explanatory information is provided for each 'monster' or design representation. The characteristics in Table 1 were drawn both from the Monster Manual [28] used in the role playing game *Dungeons & Dragons* as well as the authors' experience.

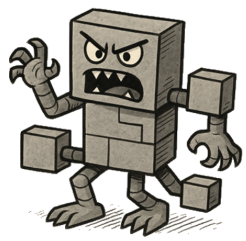
Table 1: Design Representation Traits used in the Monster Manual

Level Requirement	The level of experience/knowledge needed to use the representation effectively.
Accessibility	The chances that a non-technical audience will be able to comprehend the ideas presented on the representation.
Range	How often and where you will encounter this representation in engineering work
Complexity	The cognitive effort needed to understand, produce, and maintain the representation.
Stability	How (temporally) stable is the representation once it is created?
Initiative	when in the project lifecycle a representation contributes the *most*
Lifetime	Over what fraction of the project duration does this representation typically play an important role?
Interaction Effect	How does this representation boost or hinder other representations?
Failure Mode	the misunderstandings or poor decisions can happen when this representation is misunderstood or used improperly
Alignment	Usefulness to the different jobs or roles that make up a technical organization or company
Summoning Ritual	What tools, methods, or software is needed to create the representation
Natural Predators	Who or what often ignores, breaks, or misuses this representation?
Drop Loot	What you gain from slaying it (insight, feedback, schedule clarity).
Rumored Origins	A historical backstory or myth of how the representation first came to be created

To create the *Engineering Design Monster Manual* the authors drew from a series of short tutorials on each representation that had been created over a period of years to support the design thread courses at Bucknell. These are not yet formally published, but have been shared as KEEN cards [31]. After iteratively refining the traits shown in Table 1, values for each trait were proposed and the authors collaboratively came to a consensus decision. Further refinement and adjustment occurred as more representations were added to the *Engineering Design Monster Manual* over time, and again as comparative tables were generated. Once a traits table was generated for each representation the authors worked interactively with ChatGPT to generate images for the *Engineering Design Monster Manual*. This was the most time-consuming and frustrating process in creation of the student guide since image generation was a hit-and-miss process with significant processing delays. At least half the images created required significant touchup, which was done using the drawing programs Inkscape and Paint.net. Figure 3 shows two pages from the completed book. The *Engineering Design Monster Manual* was created in summer 2025 with on-demand publishing through Kindle Direct Publishing (Amazon) [32] and Ingram Spark. KDP allows direct access by students while Ingram Spark enables access by Barnes and Noble which manages the campus bookstore at Bucknell University. The barriers to and costs for self-publishing were minimal and allowed immediate access to the *Engineering Design Monster Manual* by students. One of the advantages of these platforms is the author can choose book pricing (limited to a minimum value) to keep costs affordable to students. A companion book with full descriptions on the representations is currently in the works.

Block Diagram

The engineering block diagram is one of the most ubiquitous and useful tools in systems and design engineering, used to represent high-level functional or signal relationships without getting bogged down in implementation detail. It is a key way to abstract a project from details to the underlying ideas.



Level Requirement	4 – easy to make, hard to do well
Accessibility	6 – abstracts technical details to be approachable
Complexity	3 - at start but gets more complex over time
Stability	2 – it is updated regularly throughout the project
Range	Ubiquitous across many professions
Initiative	Architecting the system, the block diagram is the hardware architecture
Lifetime	Long, as one of the core representations
Interaction Effect	+5 to the flow diagram, +1 on Gantt Chart and other project management documents
Failure Mode	The block diagram is as much about connections as it is blocks, not labeling or capturing connections is a common failure point.
Alignment	True Neutral, it informs all stakeholder in a project
Summoning Ritual	Miro, whiteboards, paper-and-pencil
Natural Predators	Does not play well with software elements of the project. Use other representations like Unified Modeling Language (UML).
Drop Loot	A team with balanced roles, a well architected project, ability to share your project across the organization. Also promotes a shared understanding of the project by the team – everyone on the same page.
Rumored Origins	The block diagram evolved with systems thinking in the 1930s–1950s. The concept of using symbolic blocks to represent system components began in early control theory and electrical engineering to focus more on functionality and signal flow than on wiring. Norbert Wieners cybernetics and feedback control systems (1940s) introduced the idea of systems as signal-processing units—represented naturally with blocks and arrows.

Design Abstraction Stack

The Design Abstraction Stack (DAS) is used to connect users and stakeholders to the features they need, and then to ways to implement those features through functions. Its three interconnected layers, who – what – how, capture the overall purpose a design is supposed to achieve. The DAS bridges project scoping to design activities and is helpful in connecting project scoping to design activities.

Level Requirement	5 - easy to use but requires high level project view
Accessibility	5 - speaks to designers but not clients
Complexity	6 - complicated but easy to understand
Stability	3 - added to regularly over time
Range	Rare - mostly in design-intensive and start-up firms
Initiative	Defining functions, start of convergence
Lifetime	Medium, generally abandoned when implementation starts unless there is an issue then it comes roaring back.
Interaction Effect	More complete version of stakeholder-feature model. Gains +2 from interviews and research. Boosts block diagram by +3.
Failure Mode	Not basing the DAS on interview data. Listening to yourself, not users. Failing to seriously consider alternatives for functions.
Alignment	True Neutral
Summoning Ritual	Miro or similar tools using data from interviews and research.
Natural Predators	Failing to understand the projects context. Ignorance of available technical options. Not doing the research.
Drop Loot	Much more robust block diagrams. Connecting user needs to project architecture. Explaining choices to management.
Rumored Origins	A hybrid model birthed at Bucknell from the stakeholder-feature model to steer attention to functions.

Figure 4: Images of the Block Diagram and Design Abstraction Stack representations from the Engineering Design Monster Manual. Block diagrams are commonly used engineering representation. The Design Abstraction Stack was developed internally to connect stakeholders to project implementation option.

It is important to place this work in context. First, the *Engineering Design Monster Manual* was never intended to be a scholarly contribution to engineering design or design education. It was done as a fun and somewhat humorous way to help scaffold representational fluency and schema building by providing a high-level overview to students about their choices of design representations. Second, the work was not intended as an educational intervention but rather an educational resource. Interventions are implemented changes in practice intended to cause an outcome and are evaluated on the extent to which there is causal impact of use in context [33]. A resource, on the other hand, is an artifact people use, in both intended and unintended ways, and evaluation focuses on its usability under given conditions [34]. Despite these limitations there are several contributions to design education that can emerge from this work. One is to open a space for debate on the usefulness of the characteristics of Table 1 and how they should be rated or quantified. Despite the rather *ad hoc* nature of the various categories, the act of categorization helped the authors think more deeply about design representations and how they can be used by students. The authors believe that there is space for a larger dialog on how to communicate the role and function of design representations to students. For example, alignment—which identifies which audiences the representation speaks to—offers a lens for understanding how different roles value different representations; a discussion that can be quite informative for students. In role playing games alignment is typically mapped onto a Cartesian space – e.g. good vs. evil and order vs. chaos. In the monster manual, alignment maps to a position along two axes:

- **Technical ↔ Managerial**: How directly a role engages with the mechanics and realities of engineering work versus the orchestration of people, projects, and policy.
- **Individual ↔ Organizational**: Whether one's focus tends toward the needs of end-users, operators, and field conditions or toward company objectives, risk posture, and internal efficiency.

Table 2: The depiction of alignment in the Engineering Design Monster Manual which maps design representations to tasks and roles in engineering organizations.

		Technical		
	Field Engineer Insists on visiting customers, shop floors, or test beds to understand users perspectives. Thinks failure modes are more educational than corporate success stories.	**R&D Engineer** Driven by new technologies and values internal coherence and scientific validity. Often champions feasibility studies and seeks technical depth.	**Manufacturing Engineer** Focuses on meeting technical requirements as defined by company objectives. Prioritizes internal targets such as manufacturability, throughput, or cost.	
Individual	**Technical Support** Bridges technical expertise with user contexts. Facilitates design reviews, field testing, and standards adaptation. Often serves as a "voice of use" within technical forums.	**Systems Engineer** Coordinates across sub-systems, requirements, and stakeholders. Ensures that everything integrates across tech, people, and business. A classic "glue role" in complex engineering orgs.	**Chief Engineer** Owns system architecture with loyalty to organizational priorities like scalability, compliance, and product line strategy. Often gatekeeper of technical direction.	**Organizational**
	Sales & Marketing Prioritizes roadmaps and investments based on user feedback and market needs. Pushes for alignment between user experience and strategic direction, championing underserved users.	**Program Manager** Keeps things moving. Translates between executives, engineering teams, and customers. Balances risk, schedule, and budget without taking strong ideological stances.	**C-Suite** Sets vision and allocates resources based on company performance, market position, and investor needs. Representation is strategic — filtered through metrics, risk, and growth goals.	
		Managerial		

Here is where the discussion on technical and durable skills presented at the beginning of this paper circles back – the representation statistic of alignment explicitly recognizes a space of different roles in engineering firms that require both technical and durable/transferrable skills. In other words, the skills inherent to creating and using different representations may be valued different in different parts of the organization. Thus characterizing design representations using a collection of traits like alignment can help surface blind spots in design reviews, engineering trade-offs, or even strategic planning. It opens spaces for conversations such as "Are there too many voices from the bottom-right corner (Managerial-Organizational) and not enough from the top-left (Technical-Individual)?" Table 2, above, shows how the alignment stat is depicted for students in the Engineering Design Monster Manual in terms of possible roles in an electrical engineering firm.

Impact on Representational Fluency

The *Engineering Design Monster Manual* is used as a supplementary text in the design courses at Bucknell to serve as a reference to the suite of design representations student teams use in the design course sequence. Since at the time this paper was written the resource has only existed for part of the two-semester capstone course, thus data on its use is primarily observational. This short period places significant limitations on what can be evaluated about the usefulness of the text as an educational resource, however some trends are visible. To gain some insights into use of representation below the paper qualitatively analyzed one year of weekly student reflections and the final project reports. In the year reported there were two teams of eight students each.

In terms of how useful representations were in the design process, it was helpful for teams to have a common set of representations to draw from. Analysis of team reports and the progress at design check-ins showed students did utilize multiple representations to frame and develop their design projects. In shifting from a sequential, in-class introduction to more autonomous independent reading there was no visible change in use or quality of representations. Additionally it was found that student teams were able to independently choose and modify representations that they had used in the third year design course, showing some ability to transfer [35], [36] across domains. Usefulness of various representations changed with time. Early on representations like system maps helped understand the complex societal and environmental factors surrounding their projects. As work shifted from divergent to convergent students used more structured scoping tools like the General Morphological Analysis (GMA) and Design Abstraction Stack (DAS) to narrow down potential solutions and define project boundaries. In the middle of the year, there was a noticeable shift toward technical architecture, specifically Level 0 (L0) and Level 1 (L1) block diagrams and flow diagrams as teams gained understanding of how to translate stakeholder needs into hardware and software requirements. By the end of the year representations focused on validation tools in the form of datasheets and performance metrics to compare their measured results against the expectations set in their earlier diagrams. One student noted that representations helped cement their overall understanding of the design process: *"…it [reviewing representations] has given me another chance to really think through some of our decisions and the reasons behind them. This has allowed me to refresh why we did certain things, as well as has allowed me to ask the question of was actually the best way to do it, or was it something we just chose because it was easy, or because we ran out of time and had to choose one."*

In terms of student autonomy and ownership, the extent to which students on teams, and teams themselves, demonstrated ownership of their representations was mixed. Some students and teams continued to see the act of representing aspects of their design as coursework, perhaps because of how representations were given as assignments in previous design courses. However, after several (monthly) design check-ins students began to change their practices as the fact that representations were permanent rather than transient parts of the design process sank in. This behavior was discussed by students in weekly, as well as end of semester/year, reflections on their team's progress. One team reported they started the semester creating representations using a divide and conquer approach in order to minimize the time needed to complete the 'assignment'. However. as the semester progressed, they changed their approach to develop representations as a team as they began to see how representations were used in the design process. Another team used a more collaborative approach, but this created other issues: "*While collaboration is valuable, working on the system map all together often led to confusion and disorganization. I was happy to be adding so much to the system map from all of our research but I saw that everything started getting really disorganized and overcomplicated…[the team leader] suggested that we all take the system map and make any alterations to it on a separate copy and regroup tomorrow to go over what everyone decided to change and maybe take one that everyone agrees on and edit it to make it as easy to read as possible.*" This and similar comments indicate that in creating and revising representations teams engaged in metacognitive regulation – which in turn impacted group practices and dynamics. Note that in this capstone course teams are larger than typical [11] – eight students.

There were also changes to students' representational fluency. As discussed previously a key aspect in developing representational fluency is deliberate practice with revision and feedback. Teams were required to update representations at each design check-in where they would receive formal critique; additionally informal critique of the representations was offered during class time, and students could schedule a "mock check-in" prior to the real (graded) check-in to receive informal feedback. Feedback on representation was also given as the teams submitted report drafts twice a semester. The emphasis on representations, regular feedback, and the expectation that representations were central to the design, in fact *were* the design, all contributed to students' representational fluency. Student reflections indicated the value of feedback: "*Several issues were brought to our attention on Wednesday and Friday in the logic of our system map and how different nodes connect. This forced us to rethink aspects of our system map as well as allowed us to go back and look at articles we already had documented which helped reinforce our understanding.*" Another student stated that "*The feedback we got from professors helped me see where our logic was off and how to simplify the loops made the connections clearer. I realized that too much detail makes the map confusing…*"

Additionally, the evolution of representations shows fluency increasing. Analysis of team block diagrams—one of the most central representations—shows clear improvement over time. Over a three-month period the representation changed from a conceptual functional decomposition to an implementation-level, constraint-aware system representation. The later diagram includes component specificity, quantitative values on interfaces, references to the physical architecture, and coordination metadata—all of which are hallmarks of increased fluency in engineering design representations. Metacognitively, the later diagrams highlight aspects of practical and organizational implementation by keeping the diagram aligned with design decisions and team structures. While it is certainly neither possible nor likely correct to make a causal claim about the influence of the *Engineering Design Monster Manual* in this outcome, there is certainly alignment between the intent of the resource and evidence of what learning occurred. Student reflections support this view: *"I found the Level 1 Block Diagram to be very satisfying to work on because I was able to incorporate concepts from all of our technical classes including, audio amplifiers, transmitters/receivers, microcontrollers and memory, digital/analog filtering, etc. I found that our first iteration of the Level 1 block diagram, while still in the early phases, really is a culmination of all of the advanced classes I have taken in EE."*

The continuous use of a variety of design representations as a design tool was foreign to most students despite prior exposure simply because they had never engaged in a complicated, long-term project. However as representational fluency increased at least some students began to see that even unfamiliar representations provided insights into the design process, a sign of adaptive flexibility: *"I also found that the new representations, such as the Design Abstraction Stack (DAS), were extremely useful. I'm looking forward to revising this component to strengthen our Level 0 diagram, as the DAS highlights the project's key components and functions."* This comment indicates that a desired learning goal in the class, that representations serve as assets in the design process, is at least partially met. There is also evidence that the 'representation as asset' view helped teams communicate with professors, outside observers, and clients as well as help to resolve internal disagreements on project direction: "*Our flow diagram seems to make sense, but our team had a disagreement on how the voice-recording mechanism will finish the note. We chose to split into our two desired options (a timer based note duration or a button press to start and end a note) to work on a more complete flow diagram for each.*" Another student commented that "*…highlighting the most important loops and connections in our system map and DAS. I think this really helped us present our project in an intuitive way even for someone who knows nothing about the space*." Again, such results are likely not caused by introduction of a new educational resource, but there is clear alignment between the intent of the resource to support schema development as an element of representational fluency: *"I did this by going through the block diagrams and flow diagrams in order to find the main relationships, components, and ways in which the system needs to be standardized. I found this an interesting process to be a part of, as it helped my understanding of our diagrams greatly."* Also see the quote previously on integration of knowledge through the block diagram.

The above comments also provide support for design representations as an effective method for integrating both technical and durable skills. Student reflections indicate that technical aspects of design informed, planned, and captured by representations support practice in the broad and amorphous set of durable skills required for successful engineering practice [9]. For example, one student commented "*It is always helpful to have an external individual review and judge the representations you created to confirm that your work can be distributed and make sense to others who may be even less familiar with your project.*" There were several ways that the capstone design course structured supported increasing integration of technical and durable skills. In the design check-ins design teams presented representations and discussed their design through those artifacts with questions and feedback from stakeholders. Students recorded feedback and interpreted comments as part of a process of updating their representations. Due to shifting away from introducing representations during class, the time could be used for more informal feedback on the representations which supported iterative improvement. As mentioned previously, the representations provided an object of critique that was separate from students or their actions, creating a more psychologically safe space [37]. Representations were also integrated into written reports, which were scored using a competency-based rubric. Reports were marked up and professors gave video feedback on how to better present technical aspects of the project. Teams met with clients at least every other week and were encouraged to use representations to share their progress. While the educational resource of the *Engineering Design Monster Manual* is only one aspect of a larger educational ecosystem designed to support representational fluency, it is clearly aligned with that ecosystem. By summarizing many types of representations—system maps that capture social and political aspects, interviews to capture qualitative data, and technical representations like block diagrams—it further serves to help link technical and durable skills.

Conclusion

In conclusion, this paper discussed development of a short book for students, the *Engineering Design Monster Manual*, intended as an educational resource to support representational fluency in a multi-course design sequence at Bucknell University. The *Engineering Design Monster Manual* resource was written to support a longer-term shift in the engineering design course sequence towards representational fluency. The pedagogical methods and course structures that support this shift were discussed. This paper reports on both the development of the resource as well as the environment in which it is used. As discussed previously resources need to be evaluated in context [34].

The *Engineering Design Monster Manual* serves in a large sense in the same role as a bestiary, a popular genre of literature in the medieval period which taught moral virtues through reference to real or imagined animals. In this case by providing a set of 14 classifications for engineering design representations it enables a multi-dimensional view of design representations' purpose, audience, and appropriateness. Done in a fun, tongue-in-cheek style different design representations are expressed as monsters, drawing from the genre of role-playing games. The text was designed to integrate with course structures that use design representations to help integrate the technical work involved in design with the durable skills that are important for engineering practice. It supports representational fluency by helping students practice selecting, creating, and regularly revising design representations. Evidence from student reflections and other artifacts indicate these behaviors are supported in the overall course structure, but the impact of the resource has, as yet, only preliminary evidence.

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Appendix

The table below lists all the representations in the Engineering Design Monster Manual sorted on three different criteria to illustrate how the categorization of traits allows comparison of design representations on different criteria.

Level	**Accessibility**	**Complexity**
Low Level Characters	**General Audience**	**Simpler Representation**
Professionalism	User Interviews	Form
Time Management	Project Description	Project Description
Budgets	Time Management	Use Cases (UML)
GMA	Design Timeline	GMA
Work Breakdown Structure	Form	Block Diagram
Form	NABC	Research
Project Description	Stakeholder-Feature Model	Work Breakdown Structure
Stakeholder-Feature Model	Budgets	Stakeholder-Feature Model
Research	Professionalism	Budgets
Use Cases (UML)	Use Cases (UML)	Performance Representations
NABC	Gantt Chart	UI Design
Design Timeline	UI Design	Design Timeline
Logistics & Risk Management	Work Breakdown Structure	NABC
User Interviews	Logistics & Risk Management	Agent-Function Model
Engineering Standards	Annotated Mind Map	State Diagram (UML)
Gantt Chart	GMA	Time Management
Block Diagram	State Diagram (UML)	System Map
State Diagram (UML)	Agent-Function Model	Class Diagram (UML)
Agent-Function Model	Block Diagram	PERT
UI Design	Flow Diagram	Design Abstraction Stack
Life Cycle Assessment (LCA)	Design Abstraction Stack	Logistics & Risk Management
Sequence Diagram (UML)	Life Cycle Assessment (LCA)	Life Cycle Assessment (LCA)
Design Abstraction Stack	Sequence Diagram (UML)	User Interviews
PERT	System Map	Annotated Mind Map
Class Diagram (UML)	Research	Critical Path Model (CPM)
Flow Diagram	Performance Representations	Gantt Chart
Annotated Mind Map	Class Diagram (UML)	Sequence Diagram (UML)
System Map	Engineering Standards	Flow Diagram
Critical Path Model (CPM)	PERT	Engineering Standards
Performance Representations	Critical Path Model (CPM)	Professionalism
Advanced Adventurers	**Technical Audience**	**Complex Representation**