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Mechanical Engineering Reasoning Diagram: How Can Modeling Engineering Thinking Support Learning in Writing Intensive Labs?

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Mechanical engineering reasoning diagram: How can modeling engineering thinking support learning in writing intensive labs?

The purpose of this practice paper is to suggest a mechanical engineering reasoning diagram (MERD) for equitable teaching in writing-intensive engineering labs[1]. Reasoning diagrams are designed to describe concepts and the relationships among these concepts in a structured and visual way. In order to facilitate engineering thinking among undergraduates, a MERD was developed in this study to capture engineer experts' narratives about their projects and the logic of key Mechanical Engineering (ME) concepts. The model of engineering thinking would also demonstrate rhetorical moves of the technical writing process of engineering; this mental modeling relates metacognitive knowledge to disciplinary writing. A more explicit way of teaching lab writing might have the potential to remove barriers for diverse learners, especially for first-generation college students, low-income students, and students whose native language is not English.

BACKGROUND

There is increasing interest in integrating communication into technical engineering courses. In the early 2000s, the Accreditation Board for Engineering and Technology (ABET) set effective communication as one of the evaluation criteria for engineering programs [1]. However, several researchers identified a gap between employer expectations and new engineering graduates' oral and written communication abilities in the workplace [2], [3]. The disparity is probably driven by engineering students and faculties' perception; that is, engineering is a technically rigorous discipline focusing heavily on math and science [4], [5], [6]. Due to these attitudes, students and lab instructors tend to focus more on technical knowledge rather than communication skills in labs. Another study found that the written engineering documents seldom contained socio-cultural features of engineering and the trade-offs between productivity and safety or health of an operator [7]. This type of neutral and objective text couldn't reflect the complexity and human-related real-world engineering problems [7]. In this study, we want to model engineering thinking to increase students' awareness of rhetorically-focused writing in ME labs. Many engineering programs have writing-intensive lab courses designed to simultaneously improve engineering students' disciplinary writing skills and grasp technical knowledge with hands-on lab experience [8], [9], [10].

However, barriers to teaching writing-intensive labs remain. For example, writing-intensive engineering labs have high enrollment, high grading load for instructors and teaching assistants [11], [12], and limited resources to teach technical writing in an already densely packed lab course [9], [13]. In "In Approaches to Assessment that Enhance Learning in Higher Education", Wingate [14] stated that iterations and formative feedback is a central and inevitable process for students to improve their writing skills. Unfortunately, the reality is that most engineering students are not comfortable with iteratively editing their writing assignments. Therefore, researchers suggest that guided and scaffolding peer reviews approach has a positive impact on developing engineering students' technical writing skills in lab courses [11], [12]. In addition, Geisler [15] claimed that the transition from novice to expert is mediated by academic literacy

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practices. Thus, many researchers developed new curricula using the Writing in Disciplines (WID) approach to integrate technical writing into engineering lab courses [13], [16], [17].

Engineering education scholars connect engineering thinking with the teaching of lab-intensive courses. Wolff [18] suggested engineering educators should explicitly teach students about not only disciplinary knowledge, but also the relationship between the problem solver and problem structure in different industrial contexts. Wolff [18] also pointed out that the inner discipline knowledge and outer context knowledge are intertwined as critical elements of engineering thinking. In order to find optimal solutions for human needs, professional engineers have to understand the problem context first, and then use particular discipline knowledge to solve ambiguous socio-technical engineering problems [7], [19]. When students engage in a variety of authentic engineering projects, they are more likely to develop a conceptual understanding of engineering knowledge [20], and to apply their disciplinary knowledge in the real-world situations [18], [19]. Authentic engineering projects are a type of simulated engineering work for students to learn from and practice in engineering classes. As Litzinger et al. suggested [20], the integration of project-based learning into technical engineering courses is an effective tool for students' deep learning opportunities to connect disciplinary knowledge with context knowledge.

However, connecting students with authentic engineering writing could be difficult because there is conflict for students between technical knowledge and rhetorical knowledge in the classroom. As Norgaard [21] stated, the challenge for engineering writing is rooted in engineers' competing conceptions between (1) the tangible, objective nature of engineering work and (2) the consideration of socio-cultural elements of engineering work, such as stakeholder perspectives as well as financial and time constraints. In addition, the rhetorically focused writing would create a "burden of rhetorical persuasion" in the real world of work [21]. Norgaard suggests teaching novice engineers to think and write strategically may bridge the gap between these competing conceptions, since the approach releases the pressure of the rhetorical burden from novice engineers which accompanies expertise domain knowledge. We have found a similar conceptual gap for engineering students in our labs. Thus, in our study, we suggest a model of engineering thinking as a strategic way to promote students' rhetorical skills for engineering writing.

The writing-intensive engineering lab course gives students opportunities to develop genre awareness and flexibility in writing based on specific disciplinary contexts [22]. Explicit focus on rhetorical writing pedagogies enhances students' metacognition about their composing processes [23]. Hall et al. [23] also suggested that the development of metacognition improves students' transfer of learning and facilitates engineering thinking in the real world. Furthermore, Larson [24] has pointed out that explicit and rhetorically focused writing pedagogy has removed barriers for the minoritized engineering students, particularly for first generation students and multilingual students, because of their limited educational experience in writing and different language use patterns compared with their counterparts in dominant student groups.

However, in reality, most students in engineering labs struggle to think about their writing work in lab contexts beyond their individual experience of completing the lab [25]. This makes it difficult for students to develop the metacognition about how their literacy in one practice relates to another. Another challenge in helping students transfer learning is that procedural knowledge is often tacit knowledge, and thus largely unavailable for reflection or awareness. To respond to this limitation, Lane et al. [26] showed evidence that a reasoning diagram could be used as an effective instructional tool to help students integrate subject matter knowledge with rhetorical, genre, and writing procedural knowledge. They developed diagrams in several science and engineering disciplines (e.g. Materials Science and Engineering, Computer systems) through interviews with domain experts and sample article analysis. Their findings indicated that the reasoning diagram had both experimental and rhetorical information for students to tell a persuasive story about the data they collected in the lab. Our study replicates their approach but develops a novel reasoning diagram for the field of ME and seeks to connect these reasoning maps with conversations about engineering thinking. We anticipate that by using the diagram, we will support students' development of expertise in ME by guiding them to understand how tacit knowledge experts use and structure their communication about ME projects. Diverse student learners in undergraduate engineering curricula need support beyond just access to college [27]. Using the diagram to open up experts' tacit knowledge can be especially meaningful for diverse student learners (i.e., first-gen or low-income students, students whose native language is not English, etc.) because the diagram would lower the cognitive load for these students and help support future transfer of learning.

The purpose of this paper is to present the MERD for Mechanical Engineers that we developed from our interview study with experts in the field. In this study, we conducted two-sets of 60 minute semi-structured interviews with seven ME professors at a midwestern research intensive university. The interviews focused on the experts' narratives of their research projects in ME. Using a discourse-based interview approach, we also collected a reasoning diagram from each individual. Our findings illustrated the iterative process of developing the MERD. We coded the interviews and analyzed the participants' diagrams in order to develop a general MERD, which we present in this paper. Discussion will suggest ways of introducing the diagram and talk about the implications of using the diagram as a teaching tool, including facilitating students' engineering thinking, supporting the transfer of learning, and opening up barriers to education.

METHOD

The study followed the original method established by Lane et al. [26] in their work on developing reasoning diagrams for multiple STEM fields [28]. The findings were based on discourse-based interviews with seven ME professors at a midwestern research intensive university. The interviews first identified the central disciplinary concept categories in ME and then determined the relationships between these concept categories.

Two sets of 60 minute semi-structured interviews were conducted: 1) First round interviews have two parts. The interview started with experts' narratives about their research projects in ME. Then, a series of open-ended questions were posed about the structure of the expert's work. Meanwhile, a second researcher summarized participants' narratives related to the key concepts into Table 1 in the Appendix for later use. Then, based on the content in the table above, each participant drafted a reasoning diagram that represents the key ME concepts and logics of these concepts. Follow-up questions were asked to clarify unclear text and concepts. The participants could edit directly on the draft reasoning diagram if they thought it was necessary. We kept two versions (photocopy of the original and digital version of the original) of the individual diagram from the participants. 2) The second-round interview was conducted once the coding, textual analysis, and the interactions of developing the draft reasoning diagrams were completed. Similarly, these interviews consist of two parts. The first part focused on participants' disciplinary concepts, and their patterns when they communicate their ME projects with both technical and non-technical audiences. The interview questions were designed to more deeply understand participants' tacit knowledge about the disciplinary concepts that experts use to organize their ideas about ME research and design. The second part of the second-round interview focused on participants' feedback on the draft reasoning diagram. They were asked to pay particular attention to feedback regarding the accuracy of content and the structural relationship of disciplinary concepts. suggestions for revisions were solicited for concepts, their relationships, and the visual representation of those relationships. All interviews were conducted either in the author or participant's office or via Zoom. The interviews were recorded and transcribed using auto.ai software. The research team then manually checked for the accuracy of AI-assisted transcription.

Data analysis

For the first-round interview coding, we used a blended deductive and inductive coding method. In general, key concepts in Table 1 in the Appendix were considered as parent codes, and then we developed child codes under each parent code using inductive coding. In the first-cycle coding, one researcher primarily used In-Vivo and Process coding to create code names in order to describe the data [29]. Then, the research team integrated codes into themes and drafted definitions of the themes using consensus coding. The excerpts were then ranked with numeric order from three to one indicating strong examples, typical examples, and atypical examples of the code/theme, respectively.

For the convenience of data analysis and integration of the diagrams, digital copies of reasoning diagrams were generated based on the photocopies of the diagrams. In addition, we overlaid notes from the interview on the digital diagrams when participants explained certain features of their diagrams with us during the interview. The research team reviewed all seven digital diagrams, and we decided to use one generalized diagram from one participant as a starting point. Then we focused on the similarity and the differences in the method part of each diagram because almost all participants had a method part in detail demonstrated on their reasoning diagrams. Using the same approach, we enriched the content of the generalized diagram by comparing the corresponding parts of the other six diagrams. The MERD draft was completed.

After integrating the parent and child codes from the first-round interviews, the MERD draft was expanded with commonly used disciplinary concept terms. The rhetorical moves were noted on the MERD if similar relationships of key concepts were identified in most interviews. We have iteratively developed twelve versions of the MERD after the first-round interview; this final version is the draft we brought to the second-round interview. After the second-round interview, we used holistic coding methods of the transcripts and integrated participants' feedback, resulting in four more iterations, including the second MERD draft we present here.

RESULTS

In order to compare and generalize findings from the seven participants, we summarized each of their ME projects in a structural way, including the system, purpose and context of their work (see Table 1). The following paragraphs demonstrate the key highlights of the table.

Participants focused on a variety of topics related to ME, ranging from biomechanics, to sustainable energy technology, to mechanical design, to inclusive education (see "system" column in the summary table). The diverse topics imply ME is a very broad discipline. ME professionals require multidisciplinary knowledge and skill sets. Jason described ME as a broad engineering field compared with other engineering disciplines.

> *Um If you look at what a civil engineer can do, or an aerospace engineer can do, or a uh naval architecture engineer can do, they're all, they're all almost specializations in mechanical, right? We look at things that actually exist, how do they, how are they built? How do they fail? How do I model all those processes and then everything else is pretty much a specialization, except for those crazy computer and electrical people. That's magic. ((laughs))*

Except for Chris' project, the other six projects have a specific context or multiple contexts where ME technology could apply to. In Chris' project, he used non-living cell skeletons as a model to better understand the mechanical properties of living cell skeletons. Therefore, his project is more science-based with no stated applied context. From the participants' narratives, we found that the difference among the other six participants' projects is the extent to which they used outer contextual knowledge, such as safety and economic concerns, the needs of multiple stakeholders, and social and environmental impacts of the ME technology.

Table 1. Summary of individual ME projects of each participant

	Participant	System	Purpose	Context
Science-based project	Chris	Non living cell skeletons	to understand mechanical properties of living cell skeletons	N/A
	Brian	Micro mirrors	to detect cancer cells in vivo	in clinical settings
	Anthony	Wearable exoskeleton	to improve bio performance for injured people	in therapeutic settings
	Carl	CO_2 extraction and conversion	to reduce CO_2 emission	in industry and government
	Omar	Modeling algorithms	to reallocate resources for diverse students	in preschools
	Jason	Turbocharger	to improve engine performance	in motor vehicles
Design-based project	Eric	Inflatable technology	to improve user experience	in automobiles

Based on participants' individual narratives about their ME projects, we generalized their thinking process when participants described each step to solve these ME engineering problems (Figure 1). After the second-round interview, we integrated participants' feedback into the final version of the MERD (Figure 2). As we've discovered, ME is a broad and multidisciplinary field, and the process to generalize findings is complicated with iterative revision.

Compared with the MERD draft in Figure 1, the final version of the MERD was expanded into seven parts where the research design and findings box in the draft was split into two separate boxes named "knowledge" and "methods". This change was made in order to show that a wide variety of knowledge, including both theoretical and practical knowledge, is required for professionals to design research methods and eventually solve ME problems. In addition, one of the participants mentioned that ME projects do not happen if the economics are not there. Thus,

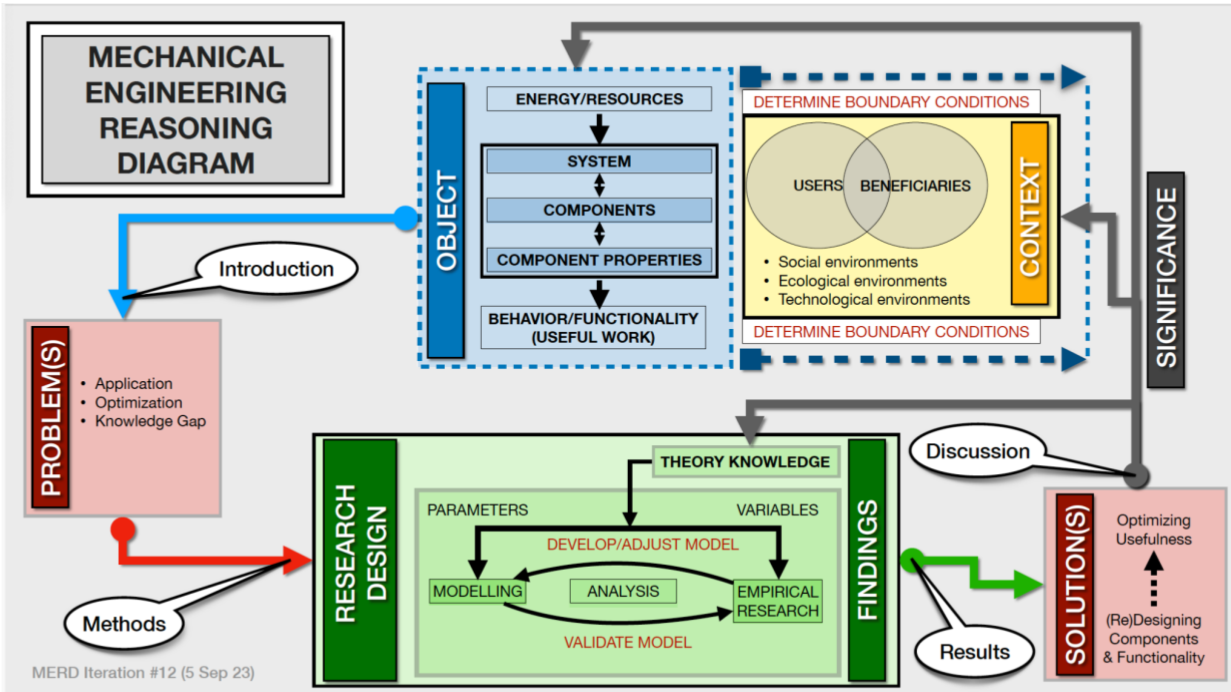

Figure 1. MERD initial draft

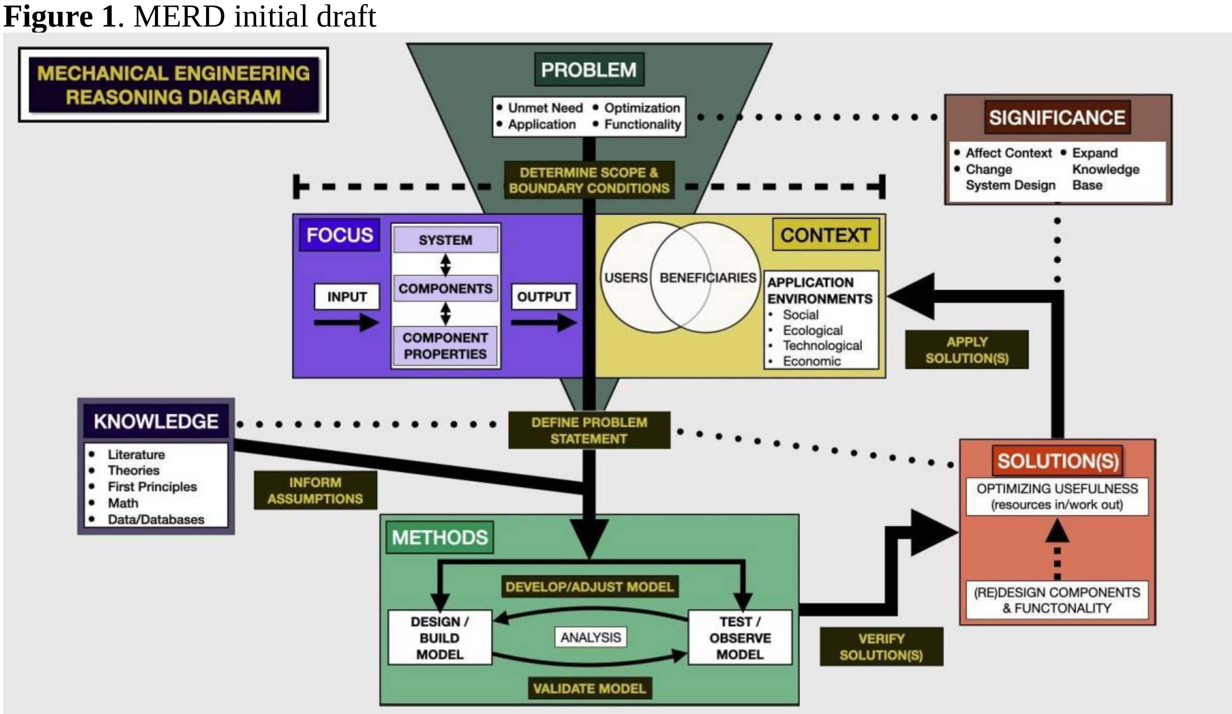

Figure 2. Final version of the MERD

we added “economic” as a new application environment in the “context” box. Similarly, we specified three aspects that the experts in ME might consider as the significance of their work in the brown box because we want to use explicit language to help students make the connection. As we’ve already observed from the first-round interview, almost all experts in our study struggled to answer the interview question related to the significance of their work.

The other important change we made was to move the “problem” box to the top of the diagram. Meanwhile, we highlighted the importance of “define problem statement” which is located in the center of the diagram. Based on participants’ feedback, professional ME should understand the problem statement clearly before diving deep into solving the problem. The problem statement determines the methods, and it is related to knowledge creation and solution (noted by dotted line). Unmet need is an additional category of problem that we found from the second-round interview data, which is a common problem for design experts.

In order to reinforce the logic movements among each box (namely rhetorical moves), we added action phrases in yellow on the arrow between adjacent boxes, such as “inform assumptions” between “knowledge” and “methods” boxes. In addition, we changed several words in the diagram draft into mechanical engineer-friendly terms. In one case, the "energy/resources" was renamed as the more general term "input" in the “focus” box. In another case, we used a more specific term “test/observe model” instead of “empirical research” in the “methods” box. In addition, we removed the genre structure of IMRaD (Introduction, Methods, Results, and Discussion) from the MERD draft, because further study is undertaking to investigate how the IMRaD structure relates to the MERD map through students writing sample analysis.

We will analyze the first three parts of the diagram (i.e., problems, object, and context) in order to learn how experts define a ME problem in a context. And then we will move to the latter four parts (i.e. knowledge, methods, solutions, and significance) where iterative design is constantly used to find the optimal solution for users/clients. In general, these seven parts are key elements to release the “rhetorical burden” when students write ME technical reports in the lab, potentially developing their rhetorical-focused writing skills in the future workplace.

1. Problem. Four out of seven participants mentioned optimizing problems as their research problem. Eric described his work as

> *Different architectures [of cells], and how can we make the best use of these architectures, and how do you design them provide the highest performing versions of the functions you're trying to create? While saving space and being lightweight, and you know, there's there's various trade offs.*

Jason focused on making efficient engines for cars. He summarized his work as

> *The more abstract version of the problem would be, when we make the engines more efficient, we have to give up something, right. So if I make it more efficient, I'm looking to lose out on power. I'm gonna lose out on transients. I'm gonna lose out on towing capacity. It's gonna be something right but the higher level is, if I want more efficiency, I have to give up something, and the goal of the project is to figure out can we get away with giving up less? ((laughs)) Right, What can we do to minimize that trade off.*

2. Focus. Participants described the focus of ME as to "transfer work and energy in motion" to do something useful, which means they calculate how much input, like energy or resources, they put into the system, and how much output, such as behavior and/or functionality, could result at the end. To design the optimal system, participants have to identify a complex system involving (sub)systems, components, and component properties. Participants described a broad range of types of systems involved in their research. For instance, the system could be interconnected technical devices in some cases. Jason worked on a complex emission system of a car which involves considering the interconnected relationship between fuel choice and engine choice when designing the system for drivers to operate the car in different ways. Brian introduced his focus of study as

> *A dynamic system in which um there is a relationship in terms of ordinary difference, ordinary or partial differential equations or a combination. That describes how if I apply an input voltage, usually as a function of time, how will that output respond as a function of time.*

However for others, the system would interact with humans, resulting in a larger complex system serving various human and community needs. Eric named the larger system "a full device/system". He gave an example of a desk lamp with safety features.

> *A desk or a, you know, a poseable lamp, you know, that you can move around or wear a safety device that pops out of the wall and, you know, helps cushion the impact or anything like that. Um the you know, the component, which is a piece of the system would be, you know, we typically look at one of those at a time and then we try to demonstrate them in more in the context of a full device or system.*

3. Context. Since most ME projects in this study are situated in specific context(s), six out of seven participants emphasized the importance of determining scope and boundary conditions for specific ME problems. The boundary conditions are used to define the problem statement in context. In Carl's CO_2 extraction and conversion project, he thought balancing among a wide range of boundary conditions set up "a really robust and holistic view", which includes a mix of economical, social, environmental, technological concerns. He constantly thinks about

> *Under what conditions, does it make sense under what conditions? Will it work economically? Are there any side effects for communities? Are there any environmental risks um that are byproducts of setting up these technologies? We need to understand that before we advise others to build factories literally*

Jason set boundary conditions based on physical characteristics (e.g., atmospheric pressure) and operating characteristics of automobiles (e.g., performance of a turbo charger) to do experiments and modeling work, but noted these parameters were also impacted by outside forces, such as government agencies. We could clearly see that the extent of using outer contextualized knowledge was important in both Carl's and Jason's projects. In summary, participants described ME projects involving optimizing problems in a complex system, which is situated in social, ecological, technical and economic environments that impacted the experts' work.

4. Knowledge. Participants named a variety of knowledge their projects were grounded on, including theoretical knowledge like math, first principles (e.g., laws of motion), theories, as well as practical knowledge from databases and literature findings. Even though all seven projects in this study were within ME discipline, two of the ME projects were also based on other domain knowledge. For example, Omar's project was closely related to social theory from

Educational Psychology and Speech Pathology. Carl's project was tightened with economic theories and hypotheses. This suggested grasping interdisciplinary knowledge is needed for professionals in ME.

5. Methods. Participants described that design/build models and test/observe models are two primary methods in ME. This process was informed by theoretical and practical knowledge, coding skills, and the ability to design and analyze experimental data. For example, Jason's and Omar's projects are heavily based on design/build models. However, Chris' and Anthony's projects focused on testing/observing the model. Brian works both sides to better understand the ME problem and apply it in context. He described the connection between these two sides as

> *They [observing/testing models and design/build models inform each other] do. Um and so (..) yeah, they go back and forth a great deal. A lot of the time they, we're just pushing forward and trying things even if we haven't really worked to all of the modeling side. Other times we do get to do fairly thorough models and use that to dictate the entire design from the stem from the starting point, so that they they [observational and modeling] do move back and forth where if we en- observe flaws in the fabrication process or limitations on what we can actually do fabrication, that may come back and put constraints on say, what are the sizes of features or what are the types of materials we can use (.) in the model in the design in the original design. And sometimes an original design will when analysis will say, Oh, if you if this (..) like let's say there's a small structure in that design, it's like if it comes out a (..) 10% larger than you've designed, that will actually substantially degrade performance. And so we should not use that that design because it's it's too sensitive to um [inaudible] so sometimes it goes the other direction as well.*

6. Solutions or goals of research. Participants described the goals of their engineering solutions as understanding the system dynamics (e.g. fundamental theories and knowledge) and/or increasing the utility of the world (e.g. applied in industries, serving human and societal needs). Brian also shared his interests in both the scientific and applied sides of the ME project.

> *I think (.) for me, it [increasing utility to the world] sort of does because I'm pretty interested in um (..) more sort of more applied sides of our of the (.) of the engineering field so like, What can new technologies from (..) research be make it into useful products effectively? And so (..), there are certainly (..) there's certainly another very common point of view is sort of, can I understand even better, why are (.) why systems um behave the way they do? And looking at and looking at the more fundamental behaviors and we're interested in that as well.*

However, Omar's work primarily focuses on understanding the system dynamics. He described his working process as

> *I try to learn how, how do classrooms that are allocated these resources in a fair way, how do, what's the characteristics of those, and then transform that into uh actionable knowledge, right? [And then he]provide feedbacks to teachers in other classrooms*

7. Significance. In the first-round interviews, five out of seven participants mentioned helping people to show the significance of their work. Two participants named developing disciplinary knowledge which has significant contributions to their feld. Omar commented on the contribution of the novel algorithm to his field and potential application in the autonomous vehicle industry.

> *These novel algorithms that hopefully will s- will be able to solve this uh open research questions in the field of dynamic systems and control of multi-agent systems, right, and, and how, how to do optimal resource allocation with diverse agents. So that that will be a contribution to the field of dynamic systems and control. That and the significance of that is huge, right? Also, I mean, because it could, um it could be uh employed to make, uh you know the autonomous vehicle, like the robot, the cars that are driving in the in the cities are they'll be autonomous, right? Make those systems more robust, or make those systems more aware of other cars, of other users, and make them m- safer, right. Um but that's not my main line of research. But the algorithms themselves could be employed for that purposes [unintelligible]*

We also noted that a few participants had difficulty answering questions like "what is the significance" or "context" of your work. This implied that they might not think critically on these two aspects of their research compared with the project problem and method. Therefore, the students in the lab might face similar struggles when solving engineering problems and communicating to different stakeholders. We expanded the question about the significance of ME work in the second round interview. The participants connected the significance of their ME project within problem context to develop knowledge and/or to (re)design the system.

DISCUSSION & CONCLUSION

Engineering thinking is used to apply engineering disciplinary knowledge to solve real-world engineering problems. For students to gain similar engineering thinking skills as professional engineers, they have to acknowledge these problems as situated in the socio-cultural world. However, students have difficulty developing the new perception of understanding engineering problems in a social context due to their limited experience and resources to access the engineering community in college curricula. In this study, we developed a MERD for students to use as a toolkit for rhetorically-focused writing and engineering problem solving. Since the MERD demonstrates strategically how our participants (experts in ME) solve engineering problems in their everyday work, we suggest a model of engineering thinking as a strategic way to promote students' rhetorical skills for engineering writing. Research has already shown that teaching novice engineers to think and write strategically would release engineering students' pressure from the "burden of rhetorical persuasion" in technical writing, which accompanies domain knowledge expertise [21]. In particular, we proposed the first three parts of the diagram (i.e., problems, focus, and context) which are essential for students to define specific engineering problems in a socio-cultural context before they jump into solving the technical problems directly. In this way, students would develop a bigger picture of the engineering problems (e.g., stakeholders, social and environmental impacts, tradeoff between efficiency and safety) rather than only focusing on experiment design and data analysis in the ME lab.

Using the MERD in the mechanical engineering lab, we want to create an authentic learning experience for students that supports their rhetorical awareness and helps them to identify genre conventions in the engineering community. The latter four parts of the MERD (i.e., knowledge, methods, solutions, and significance) displayed the rhetorical problem solving process in the ME community. Finding the optimal engineering solution requires both technical discipline knowledge (e.g., experimental design, build and test models, theoretical and practical knowledge) and outer context knowledge (e.g., understanding research goals and significance of work). As most engineering students have limited knowledge about real engineering work, they might not see the value of iteratively designing engineering solutions. Sometimes, they tend to ignore the significance of their work when designing the optimal solution, such as the attachment of problem context, the development of knowledge, and system (re)design. The MERD is a great tool to guide the ways in which students think about solving engineering problems. Thus, MERD is particularly beneficial for students with limited exposure to the real engineering world, such as low-income and first-gen college students, and students whose first language is not English.

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APPENDIX

First-round interview questions

- How long have you been working in Mechanical Engineering? How would you describe your background or research/teaching interests in Mechanical Engineering?
- How would you define the field of Mechanical Engineering to a layperson?
- What is the context of your research?
- What are the objects that you are studying/teaching?
- Who is involved in this research? Who are the researchers?
- Who are the users of the objects of study?
- What is the problem that you are trying to resolve?
- How are you researching this problem? What methods are you using? Why? What theories are you using? Why?
- What is the goal of your research? What are the desired solutions?
- What is the significance of this work?

Table 1. Disciplinary discourse chart

Key concepts	**Disciplinary** (Upper-level concepts)	**Specific** (in your field)
Context		
Object What		
Actor/Researcher Who		
User/Research subjects Who		
Problem Why		
Method How		
Theory How		
Solution/Goal Why		
Significance Why		