ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

New Orleans Jazzed about Engineering Education

Paper ID #16876

Materials Science and Engineering Reasoning: A New Tool for Helping Students See the Big Picture

Suzanne Lane, Massachusetts Institute of Technology

Suzanne Lane directs the Writing, Rhetoric, and Professional Communication program (WRAP) at MIT, is a Senior Lecturer in MIT's Comparative Media Studies/Writing department, and teaches communication in many engineering departments She also directs the associated lab, ArchiMedia, which studies how new media are shaping professional communication practices, and designs new digital tools for teaching communication.

Prof. Andreas Karatsolis, Massachusetts Institute of Technology

Andreas Karatsolis is the Associate Director of Writing,Rhetoric and Professional Communication as Massachusetts Institute of Technology. His disciplinary training includes a Ph.D. in Rhetoric and Communication with an emphasis on technical/professional communication in science-related fields, which is at the core of his teaching and research efforts. In his position at MIT and as a member of the Administrative Committee of the IEEE Professional Communication Society, he is primarily interested in designing curricula and tools which can help engineers and scientists develop life-long competencies in communication. In the past seven years he has also been the Lead of co-Principal Investigator in projects related to the design, implementation and assessment of learning technologies, especially in the domains of language learning, health communication and public discourse.

Prof. Donald R. Sadoway, Massachusetts Institute of Technology

Donald R. Sadoway is the John F. Elliott Professor of Materials Chemistry in the Department of Materials Science and Engineering at the Massachusetts Institute of Technology. He obtained the B.A.Sc. in Engineering Science, the M.A.Sc. in Chemical Metallurgy, and the Ph.D. in Chemical Metallurgy, all from the University of Toronto. After a year at MIT as a NATO Postdoctoral Fellow, Dr. Sadoway joined the faculty in 1978. The author of over 150 scientific papers and holder of 23 U.S. patents, his research is directed towards the development of rechargeable batteries and environmentally sound technologies for the extraction of metals. To push these ideas from lab bench to marketplace, he is the founder of two companies, Ambri and Boston Electrometallurgical. With recordings of his chemistry lectures broadcast throughout the world on MIT OpenCourseWare, his impact on engineering education extends far beyond the lecture hall at MIT. Viewed over 1,600,000 times, his TED talk is a narrative about inventing inventors as much as it is about inventing technology. In 2012 he was named by Time magazine as one of the 100 Most Influential People in the World.

Materials Science and Engineering Reasoning: A New Tool for Helping Students See the Big Picture

Introduction

The field of Materials Science and Engineering continues to grow, while the time to earn a bachelor's degree remains fixed, and thus, we need to continue to innovate our educational approaches in order to meet the needs of our students. The ABET criteria for Materials Engineering specifically emphasize that students should gain the ability "to integrate the understanding of the scientific and engineering principles underlying the four major elements of the field: structure, properties, processing, and performance related to material systems appropriate to the field; to apply and integrate knowledge from each of the above four elements of the field using experimental, computational and statistical methods to solve materials problems including selection and design."[1] Yet, for students beginning their studies in Materials, this integrated understanding is difficult to achieve; achieving an understanding of how new concepts and methods connect to each other can be a challenge that delays their overall understanding of Materials Engineering as a discipline. As they struggle to understand the relationship between any material's properties and the chemical and molecular structure that gives rise to those properties, they can often lose sight of the contexts in which the materials' properties matter, the patterns of relationships between materials in a class, or the reasoning that allows one to predict how different processes will transform the structure, and thus the properties, of various materials. Students also struggle with understanding experiments as part of a system of knowledge, and often instead consider their lab work as a sequence of actions involving instruments and methods in isolation. Lab reports by introductory students may fall into familiar patterns of narrative and chronology, effectively "telling" what was done—a sequence of procedures and actions—without adequately recognizing or explaining why procedures were done; even otherwise well-written reports often do not foreground the reasoning that ties the various actions together into a coherent experimental design. In short, while this integrated understanding is an excellent goal, achieving the desired functional level of integration has been a struggle for students.

This paper explains the development of a new tool, the Materials Science and Engineering Reasoning Diagram, designed to provide students with a framework of relationships between central concepts in Materials Engineering, and to integrate disciplinary knowledge and reasoning with rhetorical concepts of genre, audience, and purpose. This tool was designed through a collaborative process between faculty in Materials and those in Professional Communication, and takes the form of a visual schematic that students can use to map the relationship of concepts in an experiment; to scaffold the process of reading literature in the field; to storyboard a slide presentation or design a poster; and to outline paths of explanation for communicating technical knowledge to various audiences. The Reasoning Diagram, with a number of interactive lessons and activities, has been used in an introductory Materials Science and Engineering laboratory course taken primarily by first-semester sophomores, as well as with students writing senior theses and preparing reports and presentations on internships. Preliminary results indicate substantial differences over the course of the semester in both students' understanding of the field of Materials Science; and in their rhetorical understanding of how to communicate their disciplinary knowledge for different audiences and purposes.

Theory/background

Current research in how college students learn suggests that students struggle to understand and make use of expert procedural knowledge, to integrate knowledge from different domains, and to transfer or apply what they learn in one context to solving problems in a different context. [2, 3] While the existing educational research doesn't specifically study the problem of how students in Materials Engineering can learn to integrate central concepts and principles, and apply them effectively to new problems, it can offer a framework for approaching the problem of integration more broadly. Since the 1970s, research in cognitive science and education has studied the role of mental schemas in organizing new information and in processing knowledge gained through reading. This research suggests that identifying and activating a specific mental schema (such as a problem-solving heuristic) for complex tasks involving new information can improve the ability to integrate and successfully use that information, and it shows that we can also internalize these mental schema over time without realizing it, so that they become tacit knowledge.[4, 5] The research-based teaching approach developed by Middendorf and Pace, known as "decoding the disciplines," highlights the "bottlenecks" to learning that develop when students learn new disciplinary content but don't share an understanding of expert procedural knowledge, much of which is left tacit.[6] This approach seeks to unlock tacit procedural knowledge from experts, and make this knowledge explicit and operational by developing mental models that can be shared with students. In the field of writing studies, Beaufort identified the integration of multiple knowledge domains as one of the central challenges faced by engineering students as they learn to write professional genres and thus put their disciplinary knowledge to use.[7] In addition to knowing concepts and facts central to their discipline, and using appropriate procedural knowledge, students must also integrate knowledge about rhetoric, an understanding of the audience to whom they are writing, and a familiarity with the genres and discourse within their field. Similarly to Middendorf and Pace, Beaufort's research suggests that much of this knowledge is not taught explicitly, nor are students usually taught how to perform this complex integration. Recent research in knowledge transfer also suggests that making explicit the relationship between a discipline's ways of knowing and its central genres can help students recognize when they can connect knowledge learned in one context to a new context, or adapt it for a new purpose.[8] Making key concepts visible and helping students to reflect on the application of those concepts in multiple contexts has also been shown to aid knowledge transfer among college students writing in different disciplines.[9]

The implications of making disciplinary concepts and relationships explicit, either through the introduction of "threshold concepts"[10] or through signature pedagogies,[11] or even through the development of visual conceptual frameworks (as this paper will show) are critical for the development of students' metacognitive skills. Metacognition, in its simplest definition, is "thinking about one's own thinking"[12]. However, this "thinking" involves complex steps and practices by learners, such as the assessment of task demands, self-evaluation of knowledge and skills, monitoring progress and adjusting based on feedback to close the loop.[13] In that sense, this cycle of self-monitoring and self-control provides students with learning strategies and habits that extend beyond the content-specific and into the "meta" -- where students learn how to learn. Several expert/novice studies reinforce the significance of metacognitive skills, as they show

how experts spend more time planning,[11] or that novices continue to use a strategy after it has failed.[14] In the sections that follow we will describe our approach towards constructing a conceptual framework and will present some of the outcomes of this innovation from an introductory level lab-based class in Materials Science.

Approach

In light of this research on how students learn, integrate, and apply complex knowledge from multiple domains, our visual representation of central Materials Engineering concepts and their logical relationships attempts to ease and enable the transition of students new to the field by making the tacit knowledge of seasoned professionals more explicit and evident. Unlike the approach of decoding the disciplines, though, which aims to provide a mental model of a specific bottleneck task, the Materials Engineering Reasoning Diagram provides a visual representation for the reasoning of the discipline in a systemic manner. In addition, it shows students the relationship between the disciplinary reasoning, and rhetorical knowledge in terms of audiences and genres, which research on transfer suggests can aid metacognition and the ability to communicate in multiple contexts.[15]

We hypothesized that providing a visual illustration of the relationship between these domains would help students more quickly and easily build a mental schema of disciplinary thinking, and recognize that the task before them, in understanding and explaining laboratory work, was one of conceptual integration: of identifying logical relationships between concepts, rather than sequential relationships between actions. We also expected that students would more easily grasp that structured thought and research in this field falls into recognizable patterns that can help one understand past research and plan new research. Finally, we hoped that students using the diagram would recognize that explanations of research are always rhetorical, responding to audience, situation, and purpose, and that thus invoking the potential rhetorical situations of explanations as one does the work can aid in deepening understanding and making it more flexible. Thus, as part of a grant-funded project to develop detailed communication instruction for Materials Science and Engineering laboratory subjects, we created the Materials Science and Engineering Reasoning Diagram (for a more detailed description of the design and development of the diagram see Lane and Karatsolis 2015[16]). As shown in Figure 1, the diagram offers a visual conceptual schema of the logical relationships between central concepts in Materials Engineering, as well as structural communication paths for explaining experimental work in the field.

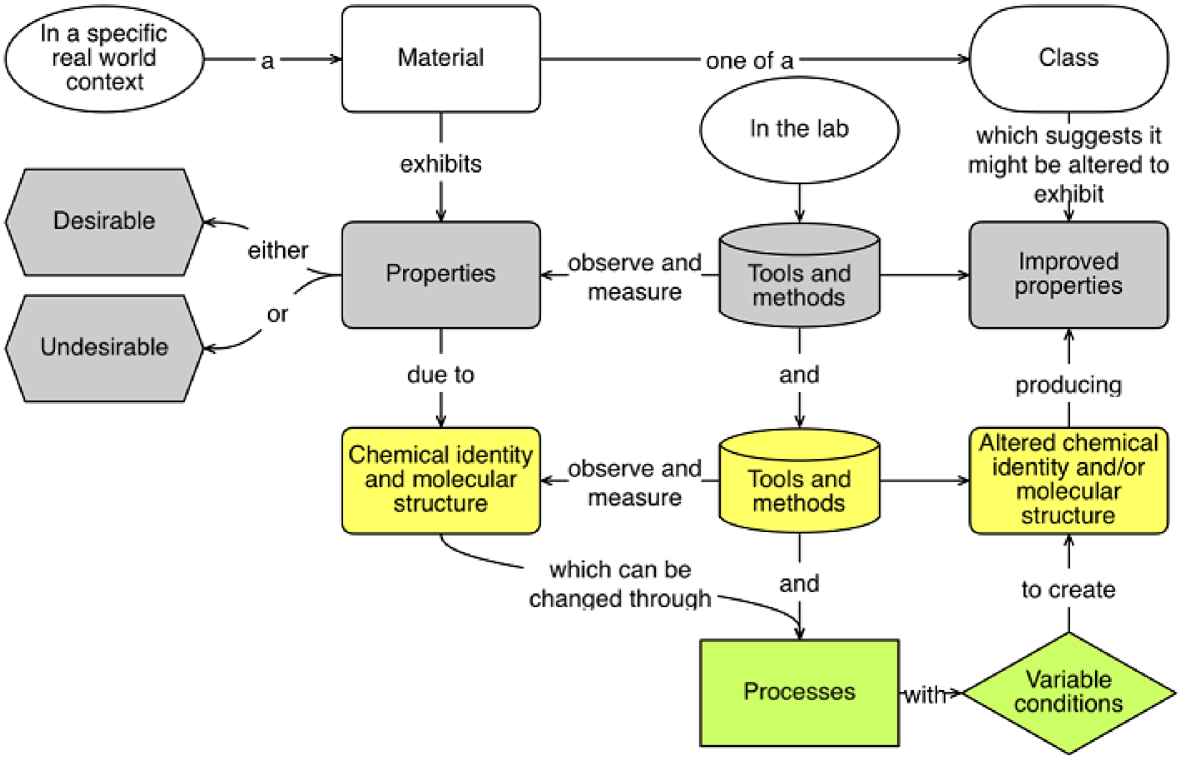

Figure 1. The Materials Science and Engineering Reasoning Diagram

At one level, this diagram shows the relationship between the "four elements" that ABET highlights: the properties, structure, processes, and performance of materials. The diagram "writes in" those relationships: properties are "due to" structure, and structure "can be changed through" processes, which would also result in altered properties. Performance, the diagram shows, has meaning primarily within a specific context; properties gain their value as desirable for specific purposes, rather than in the abstract. By focusing students immediately on these contexts, which are often missing from introductory laboratory subjects, the diagram highlights the applied nature of Materials Engineering, and helps students to recognize the contextual nature of properties. Foregrounding context also helps students to "place" the work that they do in the lab—the sequence of actions and procedures—within a purpose and reasoning-driven framework. Because each link between concepts in the diagram is both structural and syntactic, the diagram can be "read" as an abstract explanation of the basic pattern of research in the field: "In a specific, real-world context, a material (one of a larger class) has properties that are more or less desirable in that context. These properties are due to the material's chemical and molecular structure, and both the properties and the microstructure can be measured and observed in the lab using various tools and methods. The material can also be processed to produce improved properties; we can optimize the process by varying the conditions and testing the performance at the structural and property levels. The larger class of materials offers a set of somewhat similar examples, which allows us to make informed predictions about how various processes and conditions may affect the structure and properties of our specific material."

Thus, students learn that a common impetus for a project is the mismatch between known materials' properties and the desired use, and that thus the stated motivation for many different projects has a common underlying rhetorical structure. Similarly, the property-structure relationship embedded in the center of the diagram is stated as a causal relationship, as is the relationship between processing and altered properties, while the logical and syntactic relationship between a material and its class is presented as both that of definition or categorization, as well as a source of reasoning by analogy. Because the diagram helps students to both understand new material, and to communicate it, the diagram reveals the integration between disciplinary thinking and verbal articulation.

This mapping of the logical and the syntactic structure also aids students in creating their own texts about laboratory work. When the concrete details of any specific research project are mapped onto the diagram, it can be used to "write" or generate coherent and logical sentences about the specific project, as well: For example, "For use in truck axles, steel needs to exhibit external hardness to prevent wear, but lower internal hardness to provide give and reduce breakage. Since hardness is due to the carbon-iron ratio as well as to resulting molecular structure, external hardness can be increased through gas-carburized case hardening, in which low carbon steel is heated to 850-950 ºC in the presence of gaseous carbon in order to increase the carbon content at the surface, and then quenched to form a layer of martensite—a supersaturated solution of interstitial carbon atoms in the ferrite phase. Martensite is harder and more brittle than the equilibrium phases due to the body-centered tetragonal crystal structure. Initial and final hardness was measured through a Vickers hardness test. Surface hardness was increased from 110 N/m^2 to 873 N/m^2, and for a case depth hardness of 510HV, the case depth occurred at approximately 1.1mm from the surface." Thus an abstract or overview for an introduction can be generated by "writing" the specific details of a project onto the diagram. At this level, the diagram helps students make connections between one project and another, and to recognize the underlying similar pattern of reasoning, whether they are measuring the thermodynamic properties of ceramics, or performing a processing method for increasing the hardness of steel.

The diagram also helps students in their disciplinary reading practices, as a conceptual note-taking method for reading published research in the field. Because the diagram forces them to map the information from an article into conceptual categories and identify the logical relationships between them, it prevents them from extracting from the article only a vague sense of the "topic," on one hand, or a detailed list of potentially unrelated facts, on the other. We teach students to highlight the type of logical relationship that they should be able to identify between concepts, by using the diagram as a tool to critique the experimental design (or, for that matter, the clarity of the article), essentially by asking appropriate questions to uncover the logical relationships.

Finally, we show students not only how to construct an abstract or brief explanation of research by "writing" the specifics of their lab work into the diagram, but also to use the diagram to help develop both longer texts, and texts that can be targeted for different audiences. The columns of the diagram roughly map onto the sections of a journal article—introduction, background, methods, results and discussion (see Figure 2). The central concepts in each column help students to identify the "subjects"—both conceptual and syntactic—of those sections, and the links between concepts help them focus on what reasoning to develop and make explicit.

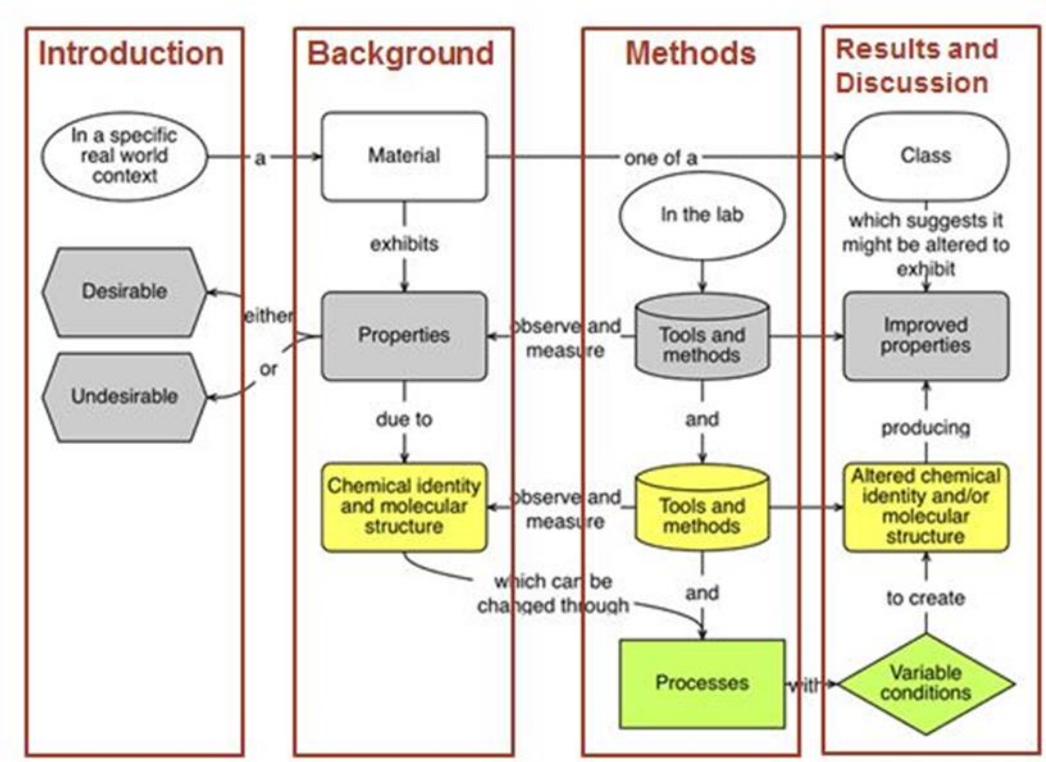

Figure 2. The sections of a research article mapped onto columns in the reasoning diagram.

If the same work is being explained to a less technical audience, however, the rows of the diagram can show students different explanatory paths (see Figure 3). For a non-technical audience, remaining on the top two levels of the diagram helps provide a clear logical line without delving into complex details: primarily explaining the material's properties in context, and the reasoning by analogy with other members of its class about why the material's properties could be altered. A more technical audience, however, is interested in much more information about the material's structure, the processing method and parameters, and the tools used to measure properties, structure, and performance. Thus, the Reasoning Diagram also shows students that the disciplinary reasoning, and the articulation of that reasoning, are always integrated.

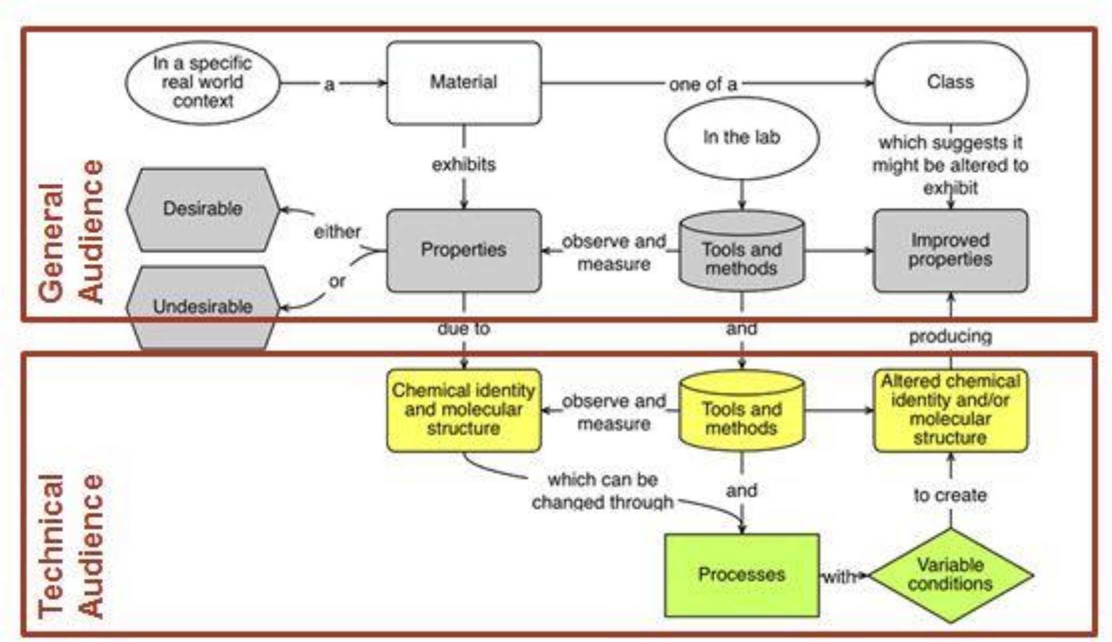

Figure 3. Lines of explanation for general or technical audiences are shown in rows on the reasoning diagram.

Results

In this section, we report on the outcomes of introducing the MSE reasoning diagram in a sophomore-level Materials Science lab course for two consecutive offerings, in the Fall of 2014 and Fall of 2015. The course was offered in parallel with a lecture class focusing on core concepts in Materials Science, including materials structure and thermodynamics. Over the course of the semester, students perform eight labs, reporting in five of them in different genres (a technical memo, a journal article, a poster presentation and two oral slide presentations). Before they begin work on their first lab, they are introduced to the reasoning diagram in a 45-minute lecture offered by the lead communication instructor. The lecture not only introduces the conceptual framework of Materials Science Engineering research, but it also presents them with a concrete example of its use, analyzing the structure of a published journal article. In addition, students are directed to a collection of online modules specifically designed for this class; one of the framing introductory modules is dedicated to the reasoning diagram, and includes a short (17 minute) video explaining its logic, and a hands-on mapping exercise in which students read a journal article and use the diagram to identify its central concepts and their relationships.

Because the MSE Reasoning Diagram was embedded in the modules, which were a new addition to the course in the Fall of 2014, we cannot completely isolate its effects on students' ability to develop appropriate disciplinary communication. However, we do have promising results from student self-reports in pre- and post-course surveys, and student focus groups, and an analysis of their performance in a final exam question asking them to produce a reasoning diagram based on a published journal article they had just been given for the purposes of the exam. Our triangulated data suggest that students showed significant learning gains in both their understanding of the field of Materials Science, and in their rhetorical understanding of how to communicate their disciplinary knowledge for different audiences and purposes.

In Fall 2014 and Fall 2015, students were asked to complete a survey in the first week of classes which asked them to indicate their level of agreement (on a scale 1-7) to a number of statements related to disciplinary communication, habits of mind and rhetorical understanding. The same survey questions were presented to the students in the final week of classes. In 2014, a total of 35 students out of 51 in the class completed both surveys, whereas in 2015 only 23 out of 44 students completed both surveys. However, we were able to compare the individual scores, as well as their averages, as reported in Figure 4. As it is immediately clear, for the five statements included in the Figure (see Table 1 for the complete statement), the results are almost identical, indicating a high reproducibility between the two offerings of the course. In addition, the "shift from baseline" between pre and post survey over the period of the 14 weeks is not only impressive in terms of percentages, but it also shows statistical significance based on paired t-tests.

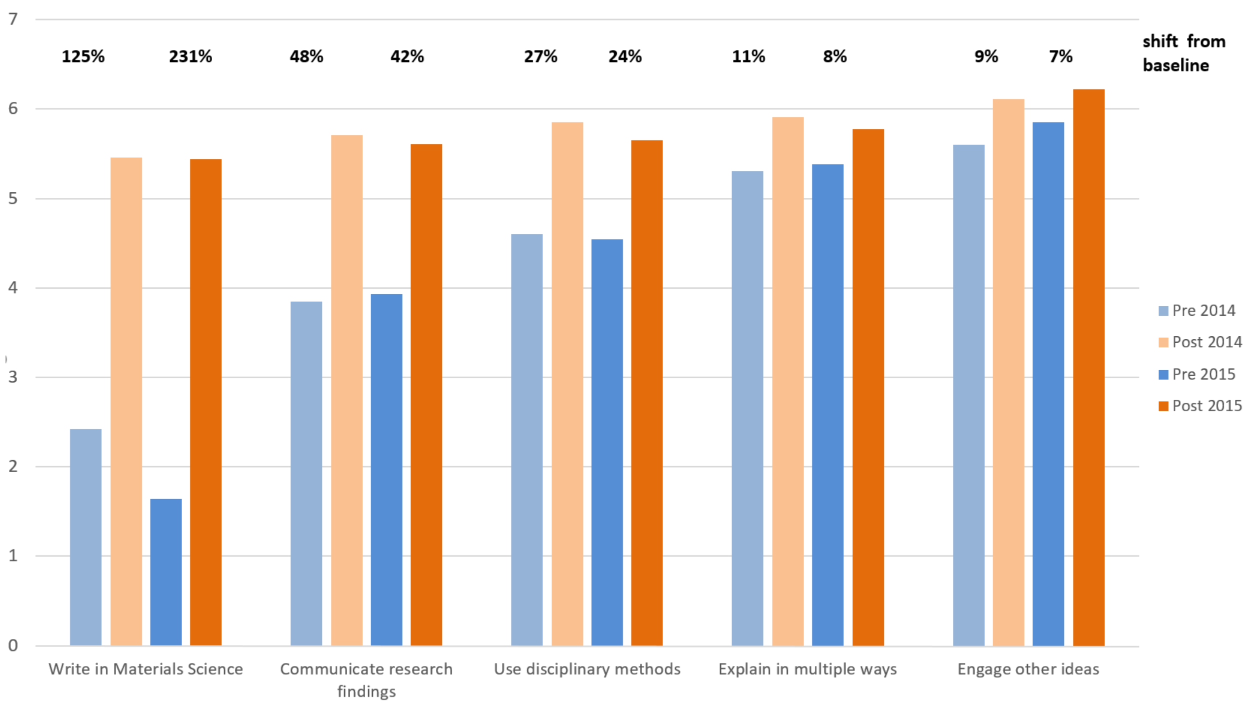

Figure 4. Change in student self-report on pre-post survey.

Table 1. The complete text of survey questions and p values.

I have sufficient experience and knowledge about writing in Materials Science
I can communicate research findings to multiple audiences using discipline-appropriate conventions
I conduct research using methods for investigating questions appropriate to my discipline
I know how to explain what I have learned in a variety of ways
I understand how to engage and incorporate the ideas of others, giving credit to those ideas by using appropriate attribution

These results showed a clear self-reported improvement of students' disciplinary understanding of Materials Science, as well as their rhetorical understanding. In fact, given that the intended learning outcomes for the course included both an improvement in the disciplinary communication skills of the students, as well as their stronger rhetorical understanding of audience, purpose and context within multiple genres, such results confirm the success of the course's pedagogical innovation. However, this success cannot be attributed to the introduction of the Reasoning Diagram, based on this data alone.

For this reason, in order to provide a better view of the how students worked with the diagram throughout the semester, and how it affected their reasoning, we also solicited student feedback from a series of focus groups with students, held a little after the middle of the semester. For the three sessions in Fall 2014, a total of 22 students attended, while 23 attended the 2015 sessions. In general, students agreed that the diagram helped them think about coherence, completeness, and structure; as one student stated, she used it "to make sure the path I'm taking makes sense," and another told us that as she was writing, she had the diagram visible so she could prompt herself to move forward in a logical development: "I would glance at it. Like, "I don't know what to write about next. I'm going to look at the diagram." In addition, they made some direct statements about its value, such as "I used it for the group presentation—that was helpful," or "I think it helped us outline the presentation, making sure we were including everything—that was good," or even just, "that was nice. I liked it." An extended comment offers insight into how the mental schema of the diagram aids in conceptual integration: "It's really clear. The flow chart format makes it a logical process. The steps are clear and logical. You can tell how one thing goes from one to another, because it's just a few words in each little box -- that has a topic, you can use that as a topic elsewhere. You can devote a paragraph to each little bubble, or even a sentence depending on the scale you want. But it sorts things into bins which is really nice if you have a lot of mush that isn't in bins in your head. Having the bins in front of you is very helpful." It's also clear that for many students, using the diagram for multiple labs and reports meant that over time, these "bins" and "paths" became second nature. One student even said that, "now, it's kind of like a guideline that's inserted at the back of my mind, when I think about presentations," while another said that after using to write in two labs, she no longer had to actually refer to the hard copy, because "I kind of had it internalized by then." A third student described the reasoning diagram this way: "I think it's very useful if you're making discoveries," but then noted that the introductory labs they were doing didn't always have a clear context, which made him think about contexts and puzzle over them, before moving on to describing the lab: "if we are testing the properties of this electrode material for a lead acid cell, then you'd be like, oh reasoning diagram. This is the material, improved properties, blah blah blah, and follow it." Given these individual responses, we included in the post-survey a few of these statements, again on a Likert scale of 1-7, to capture the overall sense of the class about them, modifying them so that they can be generalizable. The results were very encouraging, as in statements such as "The reasoning diagram was a useful tool throughout the process of writing the journal article (drafting and revising)," the average score for this question was over 5.53, with 7 being "Strongly Agree." Specifically for the statement "The reasoning diagram was a useful tool in preparing the oral presentations" the average was 5.13, even though there was no explicit instruction on how to use the diagram for the invention or arrangement of the presentations.

Student performance on the final exam also directly reveals the ways in which the reasoning diagram aided their ability to understand, integrate, and communicate research in Materials Engineering. The final was a 3-hour in-class exam with 5 central questions; 4 of these focused on conceptual and computation problems specific to the semester's lab projects, and the fifth asked students to read a journal article ("Electrochemical Determination of the Thermodynamic Properties of Lithium-Antinomy Alloys," Kane et al., 2015), diagram the conceptual relationship between its central elements, and write a brief, 75-word explanation of its main purpose and findings. As the abstract suggests, this journal article was not particularly accessible to novice students: "The variation in the high temperature thermodynamic properties of the Li-Sb system with temperature (425–775°C) and composition (xLi = 0.01–0.75) was determined by electromotive force (emf) measurements in a cell configured as follows: Li-Bi reference electrode (xBi = 0.35) | eutectic of LiCl-KCl or LiCl-LiF | Li-Sb alloy. On the basis of these data the Li-Sb couple was deemed attractive for storage of electrical energy in a liquid metal battery. In addition, an updated Li-Sb binary phase diagram is proposed." Since the students were not given the article beforehand, and could only afford to devote about 30 minutes to this final question, they needed to be able to read, decode, process, and articulate the logical relationships in the research quickly. 8 points were possible for the question, and the overall average for the question was 5.64. A representative response graded at 5, and one graded at 8, reveals the level of integrated understanding achieved by the students.

The 5-point diagram, shown in Figure 5, correctly identifies most of the relationships between the context (energy storage applications), properties (electrochemical properties and high open circuit potential due to Gibbs free energies), performance (battery function), processing (varying composition and temperature to determine phase changes), and class. A few misunderstandings are evident, as for instance, the arrow linking "electrode setups" to "phase changes." And some vagueness is also evident, as when performance is broadly characterized as "better battery function," without explaining the relationship between that and higher Gibbs Free Energy and OCP. The short abstract exhibits these slippages as well: "This study looks to characterize Li-Sb alloys in terms of electrochemical properties desirable for a liquid metal battery in storage applications by assessing the OCP efficiency as variable by phase (manipulated with temp and comp) using echem cell & electrode equipment to ultimately assess and optimize function." On the whole, however, both the diagram and abstract coherently explain the reasoning that links central concepts, and show a strong ability to read and digest new research in Materials Engineering, after just one semester of instruction. As 5 was the mode for this question, yet below the average, the 5-point diagram reveals the minimum level of conceptual understanding that most students achieved.

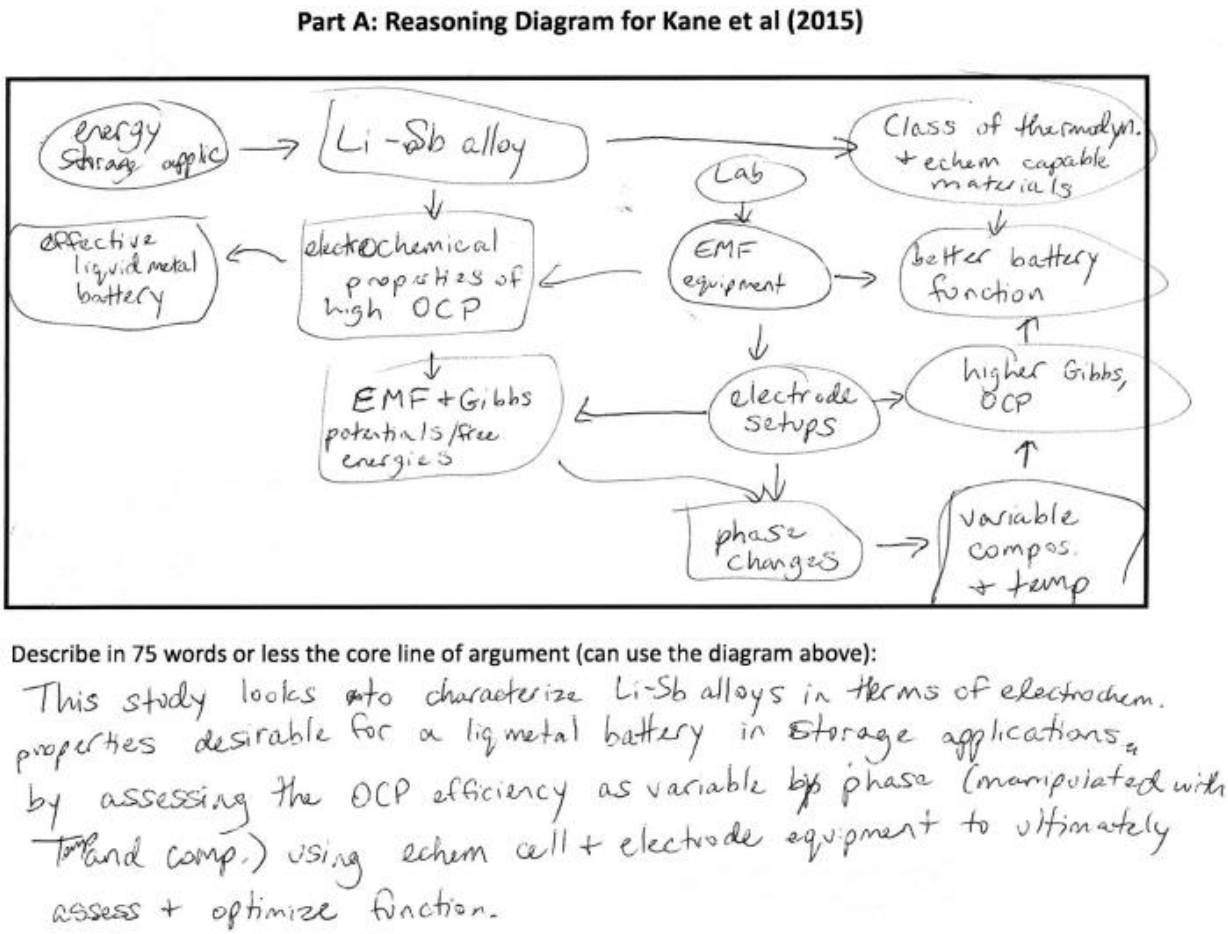

Figure 5. A representative 5-point response to final exam question.

The students who received the highest scores showed a more detailed and nuanced understanding of each element, as well as of the logical relationships between them. Figure 6 illustrates a representative 8-point response, in which the student identifies multiple methods used, from the sample preparation to the measurement of processing variables, and finally to the emf measurements, and more accurately follows the logical purpose through the experiment, from the need for a high OCP, the process of changing the electrode composition and temperature (complete with ranges for each), to determine "varied OCP measurements" and an improved "phase diagram of the LiSb system," so that appropriate temperature and composition ranges "suitable for energy storage" can be identified. In addition, as this example in Figure 6 shows, students were able to adapt the reasoning diagram as a flexible framework on which they could "hang" the information they deemed important. This student, for instance, identifies the source of existing information about properties and adds a node for the creation of a phase diagram for the Li-Sb system; other students also identified the phase diagram as a result, or added "nodes" for the Nernst equation. This sophisticated level of understanding of new research, and the ability to link the specific details of experimental methods with clear purposes in light of previous research and an overall context, shows the kind of conceptual integration that introductory students rarely achieve, in our experience, and thus suggests the role that the reasoning diagram plays in promoting this ability.

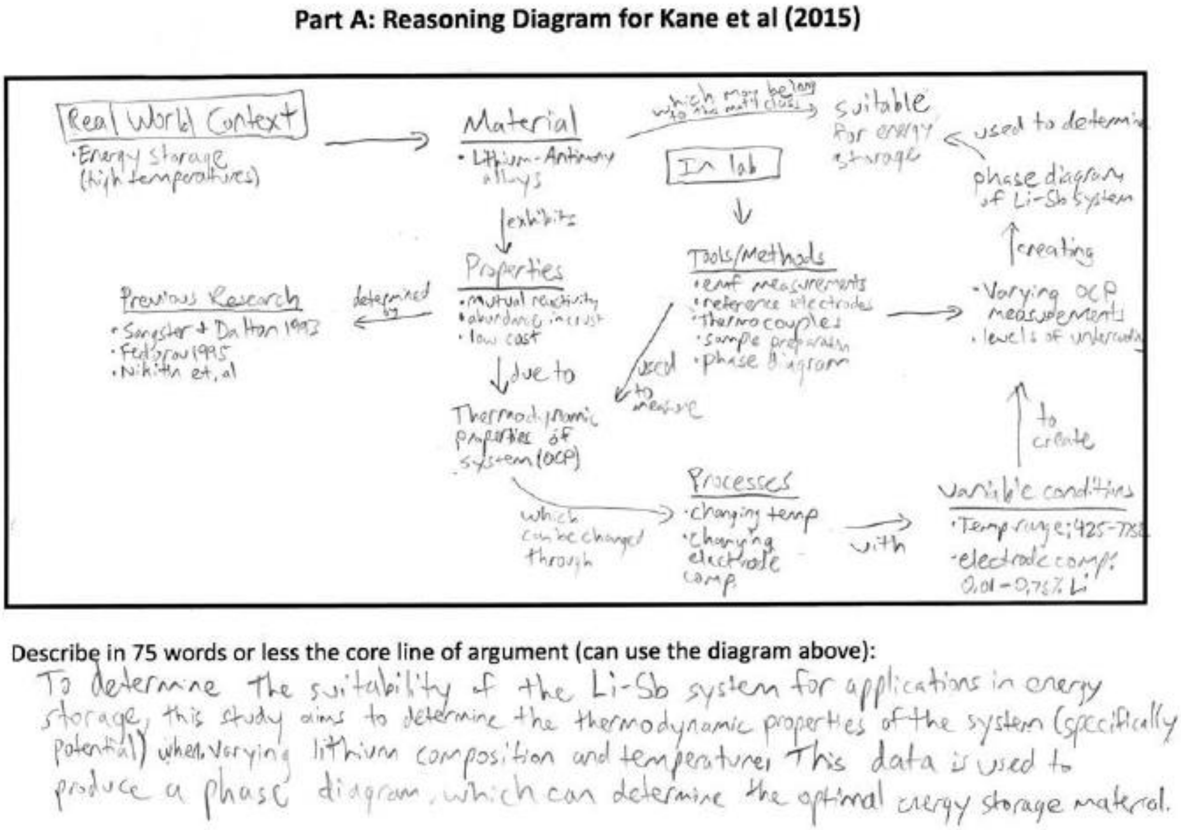

Figure 6. An 8-point final exam response. The description reads: "To determine the suitability of the Li-Sb system for applications in energy storage, this study aims to determine the thermodynamic properties of the system (specifically cell potential) when varying lithium composition and temperature. This data is used to produce a phase diagram, which can determine the optimal energy storage material."

A simple correlation between the numerical grades the 44 students received in the final exam reasoning diagram question (on a scale of 1-8) and the overall numerical grade of the final exam (on a scale of 1-100) showed a strong positive correlation (P-Value <0.01). Given the relatively small sample size, we also performed a ranked correlation, which also yielded significance with a P-value <0.01, yielding a large effect size (Spearman's rho 0.535). Similarly, we conducted analyses to correlate the reasoning diagram question in the final exam to the overall grade for the course. In this case, there was still a positive correlation with a P-value of 0.0372 and a medium effect at the 0.315 level (Spearman's rho). Both correlations suggest a high degree of alignment between the knowledge represented by the reasoning diagram, and the functional knowledge required to perform well overall in the subject.

Conclusion

While the results we provide here are preliminary, we believe they suggest that the Materials Science and Engineering Reasoning Diagram can be an effective tool for helping students to understand the underlying logical relationships between materials, their properties, structure, and potential processes for improving performance in varied contexts. It can also help students to read and understand new research in the field, and to communicate the results of their own research, effectively, for multiple audiences. To better understand how the reasoning diagram affects students' understanding and ability to both conceptualize and integrate information, further work will include textual analysis of reports and presentations, to identify the extent to which students using the reasoning diagram develop syntactic coherence through identifying the logical relationship between concepts, rather than through narrating the sequential relationship between actions.

References

1. ABET. Criteria for accrediting engineering programs. Baltimore: ABET; 2014. 27 p.
2. Novak, Joseph D. Learning, Creating and Using Knowledge. New York, NY: Routledge; 1998. 316 p.
3. Ambrose, S. A., Bridges, M. W., DiPietro, M., Lovett, M., & Norman, M. K. How Learning Works: Seven Research-Based Principles for Smart Teaching. San Francisco, CA: Jossey-Bass; 2010. 336 p.
4. Rumelhart, David E. "Schemata: The Building Blocks of Cognition." Theoretical issues in reading comprehension, ed. Rand J. Spiro, Bertram C. Bruce, and William F. Brewer. Hillsdale, NJ: Erlbaum; 1980. 586 p.
5. Johnson-Laird, Philip N. Mental Models. Cambridge, MA: Harvard University Press; 1983. 515 p.
6. Middendorf J, Pace D. Decoding the disciplines: helping students learn disciplinary ways of thinking. Hoboken: Wiley; 2004. 128 p.
7. Beaufort A. College writing and beyond: a new framework for university writing instruction. Logan, UT: Utah State University Press; 2007. 232 p.
8. Nowacek R. Agents of integration: understanding transfer as a rhetorical act. Carbondale: Southern Illinois University Press; 2011. 167 p.
9. Yancey, KB, Robertson L, Taczak K. Writing across contexts: transfer, composition, and sites of writing. Logan: Utah State University press; 2014. 185 p.
10. Meyer, J., & Land, R. Threshold concepts and troublesome knowledge: Linkages to ways of thinking and practising within the disciplines. Enhancing Teaching-Learning Environments in Undergraduate Courses. Edinburgh: University of Edinburgh. 2003. 14 pp.

9. Gurung, R. A., Chick, N. L., & Haynie, A. Exploring signature pedagogies: Approaches to teaching disciplinary habits of mind. Stylus Publishing, LLC; 2009.

11. Ambrose, S. A., Bridges, M. W., DiPietro, M., Lovett, M. C., & Norman, M. K. How learning works: Seven research-based principles for smart teaching. John Wiley & Sons; 2010. 336 p.
12. Darling-Hammond L, Barron B, Pearson PD, Schoenfeld AH, Stage EK, Zimmerman TD, Cervetti GN, Tilson JL. Powerful learning: What we know about teaching for understanding. John Wiley & Sons. 2015 288 p.
13. Chi, M. T., Hutchinson, J. E., & Robin, A. F. How inferences about novel domain-related concepts can be constrained by structured knowledge. Merrill-Palmer Quarterly, 1989. pp. 27-62.
14. National Research Council. Knowing What Students Know: The Science and Design of Educational Assessment. Washington, DC: National Academy Press. 2001
15. Koedinger KR, Roll I. Learning to think: Cognitive mechanisms of knowledge transfer. The Oxford handbook of thinking and reasoning. 2012:789-806.
16. Lane S, Karatsolis A. Engineering "reasoning diagrams": A new tool for visualizing engineering reasoning to improve engineering communication instruction. In Professional Communication Conference (IPCC), 2015 IEEE International 2015 Jul 12 (pp. 1-8). IEEE