Mapping the Relationship of Disciplinary and Writing Concepts: Charting a Path to Deeper WAC/WID Integration in STEM[1]

Suzanne Lane, Massachusetts Institute of Technology
Atissa Banuazizi, Massachusetts Institute of Technology
Malcah Effron, Massachusetts Institute of Technology
Leslie Roldan, Massachusetts Institute of Technology
Susan Ruff, Massachusetts Institute of Technology
Jessie Stickgold-Sarah, Massachusetts Institute of Technology
Michael Trice, Massachusetts Institute of Technology
Andreas Karatsolis, Massachusetts Institute of Technology

Abstract: Studies have shown that students learning to write in engineering fields struggle to integrate subject matter and communication expertise, and that STEM faculty's communication knowledge often remains tacit, rather than being explicitly taught to students. Here we show a method for eliciting and revealing tacit communication knowledge using what we call disciplinary reasoning diagrams. We offer diagrams we have developed for Materials Science and Engineering, Brain and Cognitive Science, proof-based Mathematics, and Computer Systems, and explain how they function as instructional tools that can help students integrate knowledge domains from STEM and from writing, and to scaffold their ability to think critically and communicate effectively in their field.

Introduction

In 2014, MIT's Writing, Rhetoric, and Professional Communication Program (WRAP) began a grant-funded project to develop online communication instruction modules for communication-intensive (CI) laboratory subjects in engineering. WRAP embeds communication lecturers into CI subjects, so that students receive rhetorical instruction alongside their disciplinary instruction. Our program is writing-in-the-disciplines (WID)-focused, emphasizing authentic genres of disciplinary research (e.g. proposals, research articles, slide presentations). Our instruction on genre blends English for Academic Purposes (Swales, 1990) approaches that identify textual features and conventions, such as rhetorical moves or common discourse patterns, with approaches that highlight the social actions genres perform in typified rhetorical situations (Miller, 1984)—for instance, the functions that proposals perform in the research process. We attempt to develop students' genre awareness (Devitt, 2004) and a robust ability to critically analyze, interact with, and perform genres (Bawarshi, 2003). Our program also scaffolds composing processes (Poe et al., 2010) and incorporates high-impact practices in STEM disciplines (Anderson et al.,

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2016): students write about their experiments and projects in at least two CI subjects in their major, and they perform peer review, receive instructor feedback, and revise. This embedded communication instruction is timely (students don't rely only on transferring knowledge from a writing class taken in previous semesters), targeted (instruction focuses primarily on elements that are new and challenging, and thus, in the zone of proximal development (Vygotsky, 1978)), and tailored (instruction uses authentic disciplinary examples). But we face many of the same challenges that more commonly structured WAC/WID programs face: communication instruction can still be subordinated to disciplinary "content" due to faculty concerns about coverage, and as Mya Poe et al. (2010) found in their earlier study of MIT's communication instruction, our students still saw "writing" as somewhat separate from science and engineering knowledge, and they often subordinated writing to the course content, rather than seeing the domains as interconnected.

This separation and subordination of writing is consistent with other research on STEM students learning to write in their field (Beaufort, 2007; Mallette, 2017; Winsor, 1996). Our grant allowed us to collaborate with engineering faculty to integrate our rhetorical curriculum more fully. These faculty mentioned fundamental misconceptions students held, such as "they think this course is about learning how the instruments work, but what they need to learn is how experimentation works," or "they don't understand that properties don't mean anything in the abstract, they only gain value in relation to specific contexts and purposes." Their comments indicated how they reasoned in their fields, and that they wanted student texts to reveal students' developing understanding of that reasoning. These comments also resonated with pedagogical theories about the relationship between expertise and tacit knowledge that influenced our project. *Decoding the Disciplines* (Pace & Middendorf 2004) offered us the lens of bottlenecks, places in which students can collectively struggle to understand or perform, most often because the expert knowledge they need for the task has not been fully articulated for them. Research in rhetorical studies has also explored the nature of expertise, especially in terms of knowledge dimensions and their interrelationships (Bazerman, 1989; Geisler, 1994; Kaufer & Young, 1993). More specifically, Cheryl Geisler (1994) described the development of expertise as the interaction of domain knowledge and rhetorical process, arguing that the rhetorical process dimension remains hidden for students, as they are typically taught to view texts as repositories of knowledge. Similarly, James Gee (1998, 2001) claimed that experts struggle to articulate the rhetorical process dimension of knowledge because of its tacit nature. More recently, Anne Beaufort's *College Writing and Beyond* (2007) argued that students struggle to integrate concepts and strategies from the multiple and potentially overlapping knowledge domains of rhetoric, genre, discourse, process, and subject matter as they compose.

Inspired by Beaufort's theoretical framing of the intersections of knowledge domains and by the visuals in her text, as well as by research that shows engineers typically use diagrams as part of their composing processes (Roozen & Erickson, 2017; Winsor, 1996; Witte & Haas, 2001), we decided to visualize the interrelationship of these knowledge domains. This article will explain the instructional tool, which we call reasoning diagrams, that we created to visualize disciplinary reasoning at the intersection of these knowledge domains.

The first diagram we created, for materials science and engineering (MSE), was developed through an ad hoc iterative process of analyzing model research articles, and discussions with the faculty, without a standardized methodology. We color-coded the articles to show how each domain shaped a particular text. For example, we assigned each rhetorical move of an abstract or introduction, such as "shows a gap in previous research" or "highlights significance" a different color, so students could easily see the extent and placement of each move in the text. The color-coding highlighted the sequential and structural relationship of central concepts in the field, revealing broader, field-specific reasoning patterns. We began mapping these concept relationships and asking the faculty for their reflections on our sketches; these conversations both validated our findings, and often elicited more tacit knowledge from the faculty. The process led us to articulate some tacit knowledge from the domains of rhetoric, genre, discourse, and process as well.

Iteratively reading, mapping, and discussing built consensus on a diagram that identifies relationships between central concept categories (subject matter knowledge), shows where each concept category is extensively discussed in research articles (genre knowledge), identifies different logical pathways through concept relationships for different audiences (rhetorical knowledge), and offers typical discursive relationships between concepts (discourse knowledge). Prior research on the pedagogical utility of the MSE diagram indicates that it effectively provides a scaffold for reading and composing in the field (aiding process knowledge) (Lane & Karatsolis, 2015; Lane et al., 2016).

Subsequently, we have now standardized the core components of this process and developed reasoning diagrams for other fields. We detail this methodology in the next section. In relation to the methodology, we have further refined the MSE reasoning diagram and present new focus-group results. We then present three of the diagrams developed via the new methodology: brain and cognitive science, proof-based mathematics, and computer systems. For each diagram, we describe how it has transformed our pedagogy and provide focus group and survey assessments where available. As we'll show, these diagrams have helped us make writing expectations clearer, scaffolded students' writing processes, deepened our relationships with STEM faculty, led to more integrated and explicit communication instruction, and helped both instructors and students recognize gaps in the knowledge they needed to write about their laboratory work in authentic genres.

Methodology for Creating Diagrams

To create a reproducible methodology for constructing diagrams, we adapted existing methodologies aimed at eliciting this tacit understanding of the rhetorical dimension of texts, following the *apprentice genre* of interviewing in which the interviewer is placed in an apprentice role and attempts to capture embodied, implicit knowledge from the expert interviewee. To systematically explore the tacit knowledge which guides writing choices in the disciplines and the professional world, Lee Odell, Dixie Goswami, and Anne Herrington (1983) developed the discourse-based interview (DBI). In DBIs, expert authors are asked to talk through the writing choices they have made for different patterns of discourse use at the sentence level, such as hedging (Lewin, 2005) or citation use (Karatsolis, 2016), producing important insights about novice/expert differences in the rhetorical process dimension. In some cases, DBIs have been combined with corpus-based analyses to capture tacit genre knowledge features, such as stance (Lancaster, 2016).

Our methodology expands the sentence-level scope of DBIs by inquiring about larger textual units: the sequential opening/closing of research questions (where we use the notions of open and closed as established in stasis theory; cf. Fahnestock & Secor, 1988), rhetorical moves, and the shared patterns of reasoning (following Geisler & Swarts, 2019) among a set of core disciplinary concepts, in order to synthesize the concepts and relationships into a coherent visual abstract representation. As we explain below for each discipline, we interviewed between five and eight faculty from each MIT department, using two or three of their recent research articles. The following diagram (Figure 1) captures the multiple steps of our methodology for a single participant. This methodology was approved as exempt research and interviewees gave informed consent. The project was funded by a grant from the Davis Educational Foundation.

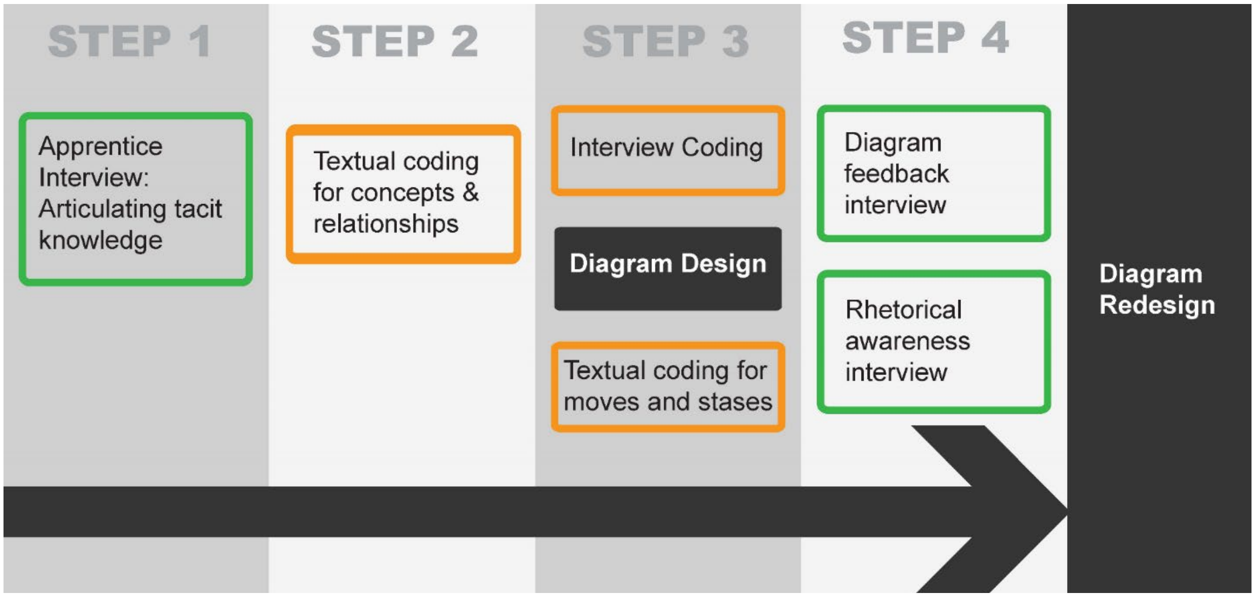


Figure 1: Overview of the steps in our methodology for developing reasoning diagrams

Our first goal was to identify the central concept categories in a field and the relationships between them. After reading the research articles and familiarizing ourselves with the projects and terminology, we interviewed each faculty member using what we call a disciplinary discourse chart (Figure 2), asking open-ended questions about the context of their research, the objects and problems studied, the theory and methods used, etc. For each discipline, we worked in pairs; one of us asked the questions, while the other took notes in the chart, and the interviews were recorded. As faculty authors described the specifics of their research, we asked them to move up one level of generalization, to identify which disciplinary concept categories their specific research addressed (for instance, their specific research might be on the stiffness of aluminum, but at a more generalized, disciplinary level, it would be about the properties of materials). At the end of each interview, we asked the faculty member to take those collected disciplinary concept terms (for instance, material, properties, processes, tools, etc.) and draw the logical relationship between them (we used Explain Everything on an iPad for this step, in order to be able to record the audio and the drawing in sync).

Context Where, When	**Object** What	**Actor/ researcher** Who	**Users/ Research subjects** Who	**Problem** Why	**Method** How	**Theory** How	**Solution/ goal** Why	**Significance** Why	*meta*
									disciplinary
									specific

Figure 2: Disciplinary discourse chart

In the next step, we used the concept terms elicited in the first-round interviews to code the articles to identify patterns of concepts, relationships, and order. Our goal was to query each participant about these concepts and the disciplinary expectations about their relationship. Mirroring the DBI model, the concepts that we identified were then turned into multiple two-part questions of the form: “We saw in coding your text that these concepts (c, f, g) were the primary focus and received the most space, while these concepts (a, d) weren't mentioned explicitly or received little space. Would it have made a difference if those concepts had been included or expanded?"

As we developed our methodology, we realized that the syntactic connection between two concepts in a reasoning diagram form a proposition that resides in a particular stasis of fact, definition, causation, value, or policy (Fahnestock & Secor, 1988). This realization allowed us to map the stases onto our diagram, to illustrate what type of claim occurred at each link, and thus, what type of evidence was required to support that claim. Stasis theory also helps to analyze the relationship with the audience; if the audience is in agreement with us (that is, the stasis is closed), we spend comparatively less space explaining and supporting the claim, leaving more space to develop the open stases, in which we are arguing new knowledge into place. Thus, we coded for the order of stases, for whether stases were open or closed in the text, and for rhetorical moves, and we created similar two-part questions based on these characteristics. Based on these textual patterns from the coding, as well as structural patterns that emerged in the participant's own sketches of concept relationships, we began iterating on the visual representation of the discipline's reasoning patterns. Given that we had to synthesize the interview data from up to eight participants for each discipline (and their coded written texts and the sketches), this was the most time-consuming step.

In the fourth step, we returned to the participants for an hour-long interview in two parts: first, we asked the questions about concepts and their order, then about the order of stases and rhetorical moves (both moves that were present in the article and ones that were absent). These questions elicited tacit knowledge about audiences, genres, and reasoning. After that, the participants viewed the draft diagram; commented on its accuracy and structural relationship of concepts; and annotated it for missing concepts, relationships or any visual grammar issues. Exploring the diagram allowed for reflection by the participants on their own disciplinary practices and assumptions, a part of the interview which they reported as useful and enjoyable.

The participants' feedback on our diagram draft enabled us to redesign the reasoning diagram of each field and begin bringing it into classrooms, as explained in the next sections.

Results

Redesigned MSE Diagram: Telling a Coherent Story

Our revised MSE diagram (Figure 3) shows that materials and their properties and structures are analyzed in the laboratory, but the properties are evaluated in a specific context of use. This context drives the need to improve the properties or develop new materials. By analyzing and understanding the chemical and molecular structure, as well as understanding the relation of the material to other members of its class (e.g., polymers, metals, ceramics), a researcher can begin to reason by analogy about the types of processes that would alter the structure and thus improve the properties. These two lines branching from "material" form the foundation for predictive reasoning about the design of new processes, which is then in conversation with the third main line, that of the experimentation, starting from "in the lab." When we discussed this predictive reasoning while planning instruction, one of the professors realized that he has his professional colleagues as dialogic audience "embedded" in his head, so that he anticipates what questions they will ask and evidence they will need to be convinced as he is designing experiments.

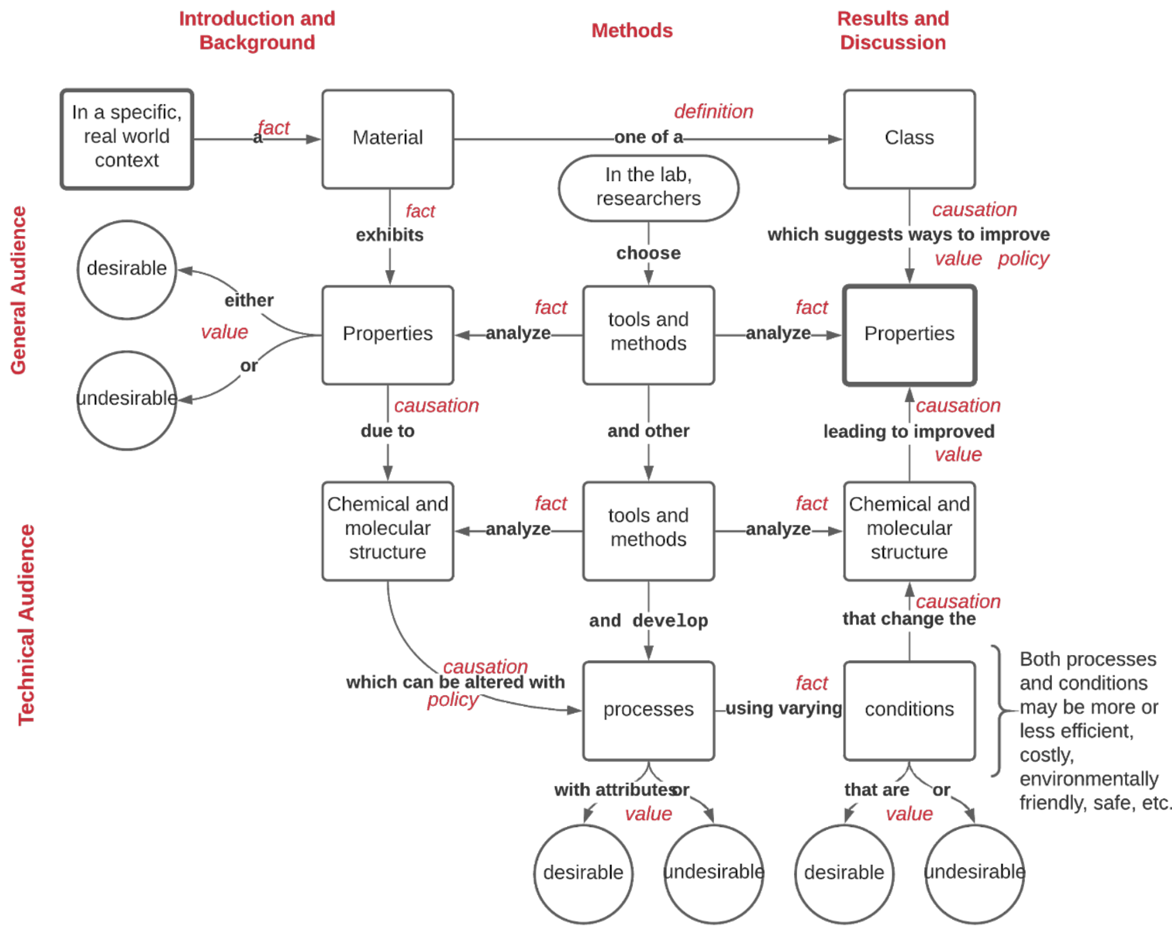


Figure 3: Revised Materials Science and Engineering Reasoning Diagram. The concepts are arranged in columns, roughly aligned with subsections of a research article in which those concepts are most prominent. They are also arranged in rows, with lower rows corresponding to greater depth of technical specificity. The arrows offer differing logical and syntactic pathways one might take through the concepts in relation to the level of expertise of the audience. The stasis of each noun-verb-noun proposition is marked in red italics. Circles are used to represent attributes of properties, processes, and conditions.

As importantly, the diagram reveals useful insights about how to communicate research to audiences. At one level, the specifics of a project can be mapped onto the diagram at a high level of abstraction, to form the basis of an abstract. At another level, zooming in to focus closely on any relationship between two concepts allows for the development of more complex, extended prose and persuasion. For instance, in the background section, one might develop a paragraph about how the chemical and molecular structure of the material results in its particular properties. The diagram reveals some organizational features that novices often miss as well. The "in the lab" line shows the need to structure the methods section to group tools and methods that analyze properties separately from tools that analyze structure, and from processes. This visual separation helps students clarify these distinctions, as novices frequently write about methods in the order they were performed, rather than conceptually organizing them. The diagram also reveals the "horizontal" interconnections that need to be developed between the background section, methods section, and results and discussion. Since students typically struggled to make these cross-section connections (as Poe et al., 2010 also found for students in a Biology laboratory CI course), and to logically categorize and sub-head their background, methods, and results sections, the diagram usefully reveals that the texts they write are nominally linear, but the underlying logical relationships between concepts within the text form a networked structure of claims.

As compared to our original diagram (Lane & Karatsolis, 2015; Lane et al. 2016), we've identified a few additional values claims in relation to the processes and conditions that are significant features of reasoning in this field, even though they are often only briefly or subtly discussed in the texts. The existence and subtlety of these values claims in STEM discourse have been analyzed by Jeanne Fahnestock and Marie Secor (1988) and Michael Carter (2016). Yet, understanding the trade-offs between potential improvements in a material's properties (or the development of a new material with desirable properties), and the cost, safety, time-scale, etc. of the processes that produce those improvements, is part of maturing as a professional engineer.

Each year from 2014-2017 and in 2019, focus group participants were recruited from the MSE lab class. The focus groups were held mid-semester, after students had completed three assignments. Over the five years, 103 students participated. Participants were asked a series of open-ended questions: when was the reasoning diagram introduced to them? Did they use it? Why or why not? How? As they wrote? As they planned presentations? What were the physical and conceptual ways that they used it? Was it helpful? In what ways? Follow-up questions were asked for clarification, and if responses seemed to converge, a show of hands was requested to assess the relative agreement. The focus group protocol was approved as exempt research and participants gave informed consent; focus group sessions were recorded for later verification.

Results from the 2014 and 2015 focus groups have been previously reported (Lane & Karatsolis, 2015, Lane et al., 2016). The focus groups helped us understand how students experienced the reasoning diagram as an instructional tool. Over the years, common phrases emerged: "I had this in the back of my mind," "it helps you know what should be in each section," or, more complexly, "because we have to write and think about what goes in each section, the diagram helps to think about what you have to focus on in each, but then it also shows you what you have to connect that to." Students also said, "the point of the reasoning diagram is to be able to tell a coherent story," and "at first it was confusing, but it made me realize there's a lot to consider. It's not just that you have to talk about each node, but you really have to think about all of the connections and how to support them." Students recognized the need for coherence and logical connections between concepts, as well as the relationship between claims and evidence, and reported that the reasoning diagram spurred their thinking about these issues.

By 2016, in order to encourage predictive thinking, many lab instructors had incorporated the diagram as part of the pre-lab activities, having students map the information for the upcoming lab onto the diagram. Across the board, in the focus groups students reported wanting feedback on how they had mapped information onto the diagram, as they recognized that there were multiple ways to do this. In addition, two lines of comments emerged. First, students requested a rewritable or interactive version of the diagram, and that we offer a less developed version that they could elaborate on themselves. Second, students were becoming increasingly critical of gaps that they saw as they tried to map information and reasoning from their various lab experiments onto the diagram. As one student said, "Sometimes it was easy to see the real-world application, and for other labs it seems like it's really only about methods, and just figuring out how one instrument works. And sometimes we don't even have our own data." Another noted that the reasoning diagram "is a useful way to think about the relationships. The only thing is, the labs vary so much in what they give you and what they want from you—not all of them give you what you need for the context, for instance, and some don't actually have you process anything." When asked about these gaps and how they dealt with them, students explained that they did extra research to fill in the gaps, so they could tell "a coherent story." A number of students mentioned that they learned quite a bit researching to fill these gaps, and felt they consequently had a better understanding of the work of Materials Science. Students repeatedly raised the issue of audience during these discussions, anticipating the need to make reasoned connections between the concepts and information, to fulfill the genre and discourse community expectations. The reasoning diagram thus scaffolds the integration of knowledge domains, and led some students to become more independent researchers.

Brain and Cognitive Sciences: Identifying Research Questions

The Brain and Cognitive Sciences (BCS) Reasoning Diagram (Figure 4) maps the concepts and their relationships for two interrelated disciplines, brain science (hereafter, Neuroscience; the discipline includes the subdisciplines of cellular/molecular neuroscience, systems neuroscience, and computation) and cognitive science. The outer ellipse reflects the scientific method utilized by researchers in both disciplines, while the gray-filled oval outlines their objects of study, arranged in columns as a hierarchy of increasing specificity. Neuroscientists experiment with the brain structures listed in the center column, while cognitive scientists analyze the processes in the left column. Both types of scientists measure physiological changes (right column) to understand how a neural system processes information to generate behavior.

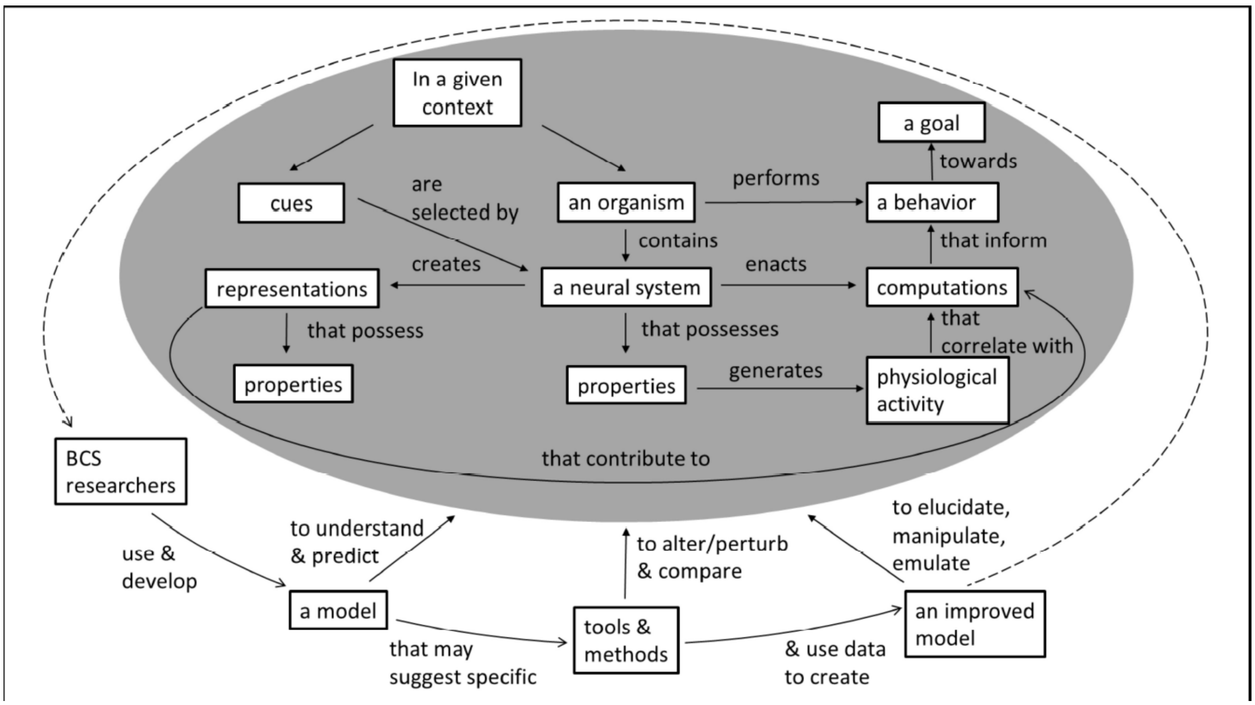


Figure 4: Brain and Cognitive Sciences (BCS) Reasoning Diagram. The gray-filled oval encompasses the objects of study of scientists from two related disciplines: the physical elements of the brain structure (center column) analyzed by brain scientists; and the processes (left column) investigated by cognitive scientists. The outer ellipse includes the researchers and the concepts developed through disciplinary research (e.g., methods and models). Within the gray area, concepts are arranged in columns, where the center column are the physical features, arranged in a hierarchy of increasing specificity, that cause the functions at the cognitive (left column) or physiological (right column) level. Relationships between columns are primarily causal, while relationships within the center and left columns are primarily categorical or definitional.

We used the BCS Reasoning Diagram to guide students in reading and writing peer-reviewed research articles in a junior-level neuroscience laboratory course, where students learn about methods and logic in neuroscience through hands-on experience. Due to the subject matter, students focused on the concepts referring to the physical features and their corresponding physiological functions (center and right columns, respectively, in Figure 4). Our findings below are based on the experiences of one of the authors.

The Reasoning Diagram enables students to navigate unfamiliar terminology in journal articles. The organization of the objects of study teaches students about two lines of logic. First, the two columns reveal the underlying assumption that structure (center) determines function (right). Neuroscientists alter structure, observe the resulting change in the corresponding function, and then use these changes to make inferences about the processing of information. Second, the levels within the columns help students understand that although all neuroscientists ultimately study how an organism performs a behavior (top level), neuroscientists use a reductionist approach, focusing on a single neural structure and an underlying component or property. Neural structures can be studied at a variety of levels (in order of decreasing scope: brain, region, neuronal network/circuit, neuron, synapse, protein), and the structure's properties are one level below the neural structure. For example, a systems neuroscientist may modify a region in order to understand its function in the brain, or change a neuron in order to elucidate its role in a circuit. On the other hand, the biggest neural structure studied by a molecular and cellular neuroscientist is a neuron.

Using the Reasoning Diagram to follow the logic of journal articles helps students understand which concepts to map. Neuroscience students do not have to concern themselves with the cognitive processes in the left column; nor do the experiments alter both the context and underlying property of a neural structure. In addition, students easily identify the organism being studied, but may take more time in determining the relevant neural structure and context or property that is modified. To assist them with this process, we composed the following discipline-specific generic language to enable students to "read" the Reasoning Diagram: (1) Neuroscientists use and develop a model to understand how a neural system contributes to a behavior (Introduction); (2) The model suggests tools and methods (Methods) to alter the context or properties and to compare the resulting behavior or physiological activity (Results), respectively; (3) Neuroscientists then use the data to create an improved model to elucidate how the neural system contributes to behavior (Discussion). Such language can aid students in establishing the neural system, how it was studied, and how experiments are typically reported within a research article.

In utilizing the Reasoning Diagram to facilitate the students' writing process, we discovered, as with the MSE diagram, mismatches between the course experiments and professional research illustrated in the diagram. Such mismatches complicated students' efforts to compose a coherent article. For example, professional scientists address questions with an open stasis, but students in teaching laboratory courses investigate questions whose stasis is closed. Thus, students may believe the goal of their experiments is to show the utility of a method, but the procedure is normally used by neuroscientists. Alternatively, students may study the role of a neural structure, but the role is already well characterized. Students will therefore find it difficult to articulate the gap addressed by their experiments. In addition, experiments may lack important controls, or may involve unrelated components of a neural system (e.g., two neurons that do not belong to the same circuit). In such cases, students need additional support in identifying a research question and selecting relevant data to present. The Reasoning Diagram may therefore reveal what students need - experimentally and rhetorically - to build a persuasive story about the data they generate.

The Reasoning Diagram offers other ways to help students focus and structure their texts, and recognize and address the gaps in their logic. For example, when they determine the stasis of their research question, are they investigating whether a neural structure has a particular property (definition), or the role of that property in the function of the neural structure (causation)? In addition, students learn to decide how individual experiments address their overall research question. For example, students may wish to group together observations of behavior, or observations of physiological activity. Finally, by ascertaining the neural structure they study (e.g., neuron circuit or synapse) and the context or property they alter, students understand that they need to review what is known about these structures in their Introduction section, or expand upon the impact of their research on these concepts in the Discussion. Therefore, these concepts are used as search terms while gathering literature to justify the project or argue the significance of the data.

Identification of these concepts also emphasizes the intellectual framework of their study: students investigate a process regarding human behavior, rather than demonstrate the value of a standard neuroscience technique.

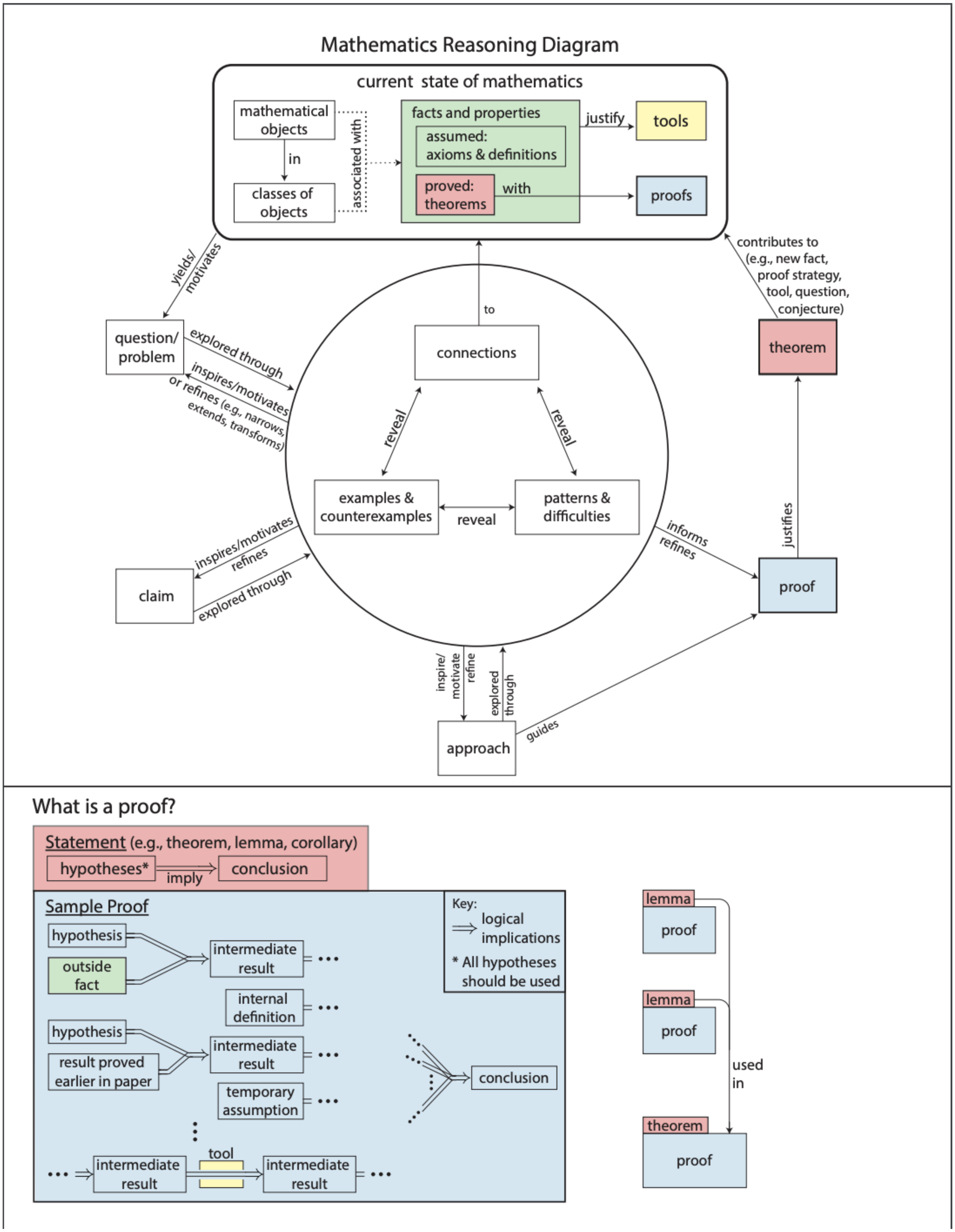
Mathematics Reasoning Diagram: Integrating Domains Explicitly

The mathematics reasoning diagram is based on textual analysis and interviews with five experts who together represent a wide range of subdisciplines: number theory, logic, algebra, analysis, theoretical computer science, combinatorics, and geometry. In these subdisciplines, the primary form of argument is deductive reasoning, or proof. The mathematics reasoning diagram (Figure 5) maps both the role of proof within the reasoning patterns of mathematics (the diagram's upper part) and the deductive reasoning of proofs themselves (lower part). The diagram illustrates that the current state of mathematics yields questions or problems, which mathematicians tackle by building intuition (the inside of the circle), e.g., by generating examples and counterexamples, looking for patterns and articulating difficulties, and recognizing connections to existing knowledge in the field. Building intuition may result in a belief, or claim, about what is true, and may yield an approach to a proof; or difficulties may cause the researcher to modify the question or refine the claim. If a proof approach yields a rigorous deductive proof, which is illustrated in the bottom part of the diagram, then the claim is stated formally as a *theorem* and enters the current state of mathematics, along with any new questions, proof strategies, or tools that were developed to yield the proof. Because arguments in mathematics are deductive, stases in the diagram are limited to those of fact and definition, so stases are omitted from the diagram.

Like the other reasoning diagrams, the mathematics diagram enables pedagogical integration of the domains identified by Beaufort (2007). The content domain is reflected in the mapping of disciplinary concepts. Genre conventions are revealed by the central circle: concepts that build intuition appear relatively rarely in research articles, but are included frequently in expository articles. Furthermore, excluding proof, the flow of concepts around the outside of the circle approximates the flow of a research article introduction; the proof then comprises the body of the article. As the proofs of many theorems require proving intermediate claims, mathematics has a discourse convention of simplifying a complicated proof by breaking part of it off as a separate proof, called a lemma; this discourse norm is illustrated in the lower right of the reasoning diagram. The intuition-building concepts inside the circle scaffold the invention process, both for those students first learning to write proofs and for more advanced students doing mathematics research. The bottom part of the diagram illustrates how arguments work in mathematics (rhetoric domain) by drawing the deductive logic of a generic proof.

Before creating the reasoning diagram, we occasionally used the drawing of a proof's logic to integrate instruction in rhetorical strategies with the mathematics content that students were learning, but our instruction rarely integrated more than a few domains at a time. After we created the mathematics reasoning diagram, we increased the use of proof drawings in our pedagogy and, for the first time, drew the logic of a paper-long proof. Doing so caused us to recognize that such a proof drawing can be used to integrate our instruction in the content, rhetoric, discourse, genre, and process domains, as illustrated in Figure 6.

For the content domain (black), the statements in boxes in Figure 6 represent either stated or implied claims in the proof, while the arrows show how initial statements combine deductively to obtain intermediate statements, which combine deductively to obtain the proof's final conclusion. As the colors in Figure 6 show, we layer other domains over the content, visualizing their integration. The rhetoric domain (blue layer) illustrates how students can help readers follow a proof's logic by structuring the proof into several logical threads. The orange layer highlights the discourse domain by visually separating an intermediate claim and its proof into a lemma, and the genre domain (green layer), which calls out core features of a math research article introduction: a statement of the paper's main result and advanced organization.


Mathematics Reasoning Diagram
current state of mathematics
mathematical objects
in
classes of objects
associated with
facts and properties
assumed: axioms & definitions
proved: theorems
with
justify
tools
proofs
yields/ motivates
question/ problem
explored through
inspires/motivates or refines (e.g., narrows, extends, transforms)
to
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reveal
reveal
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theorem
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inspire/ motivate refine
explored through
approach
guides
What is a proof?
Statement (e.g., theorem, lemma, corollary)
hypotheses*
imply
conclusion
Sample Proof
Key:
logical implications
* All hypotheses should be used
hypothesis
outside fact
intermediate result
internal definition
hypothesis
result proved earlier in paper
intermediate result
temporary assumption
conclusion
intermediate result
tool
intermediate result
lemma
proof
lemma
proof
used in
theorem
proof

Figure 5: Mathematics Reasoning Diagram. In the upper part of the diagram, the concepts outside the circle flow counter-clockwise from the current state of mathematics, through the process of developing new proofs that then contribute to the field. This path aligns roughly with the structure of a research article, while the concepts inside the circle relate to building intuition and understanding, and are more often included in expository articles. The arrows offer differing pathways through the concepts. The lower part of the diagram presents argumentation in mathematics: deductive proof. As illustrated in the red "Statement" box, any statement that can be proved can be written in the form "If [hypotheses], then [conclusions]." A proof (blue box) uses the statement's hypotheses, outside facts (green), previously proved statements, and tools (yellow) to logically imply (double-line arrows) the statement's conclusions, usually via intermediate statements. The color blue elsewhere in the diagram indicates that all proofs follow these logical constraints. The colors green and yellow indicate that outside facts and tools used in a proof are taken from the current state of mathematics, while the repeated color red indicates that the red theorem and lemma boxes that appear throughout the diagram are examples of statements that need proof. The proof tree at the lower right roughly aligns with the structure of the body of a research paper and shows how proved lemmas can be used within the proof of a paper's main theorem.

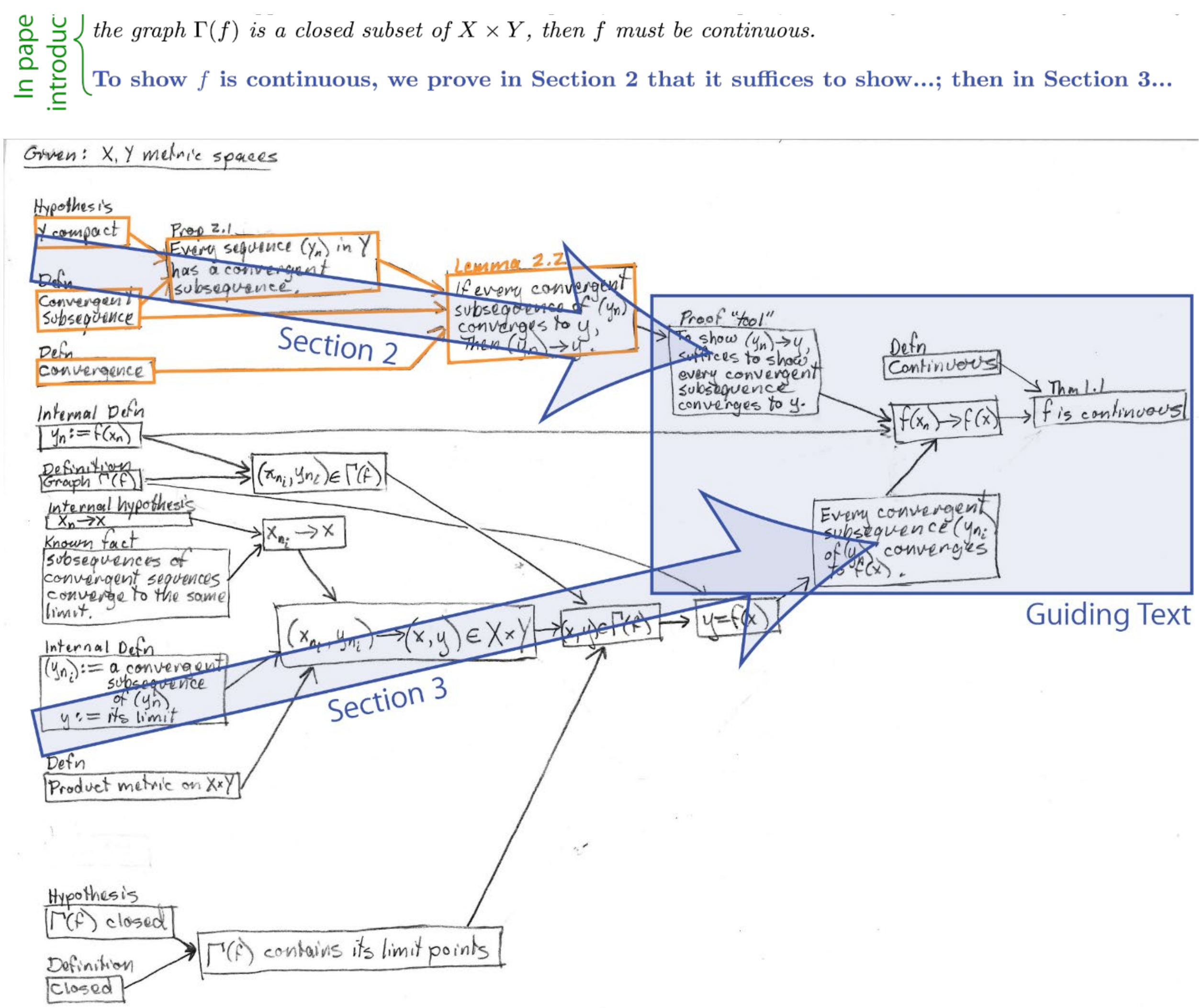

Figure 6: Materials used during instruction in writing mathematics papers. Short excerpts from a paper's introduction show the statement of the paper's main result (Theorem 1) and guiding text outlining the paper's structure. These are juxtaposed with a drawing of the logic of the theorem's proof, with overlays indicating how the logic relates to the paper's structure. Colors have been added here to highlight how Beaufort's domains are integrated in this pedagogy. Black refers to the content domain, blue rhetoric, orange discourse, and green genre.

For the process domain, we tell students that they can refine their understanding of the proof by drawing the underlying logic as illustrated in black here, and they might find this drawing to be helpful as they decide which lemmas to pull out and how to use text to guide readers through the proof's logic.

We discuss a slide like Figure 6 as the culmination of an 80-minute class workshop on writing math papers. We find that the proof diagram enables us to integrate our teaching of these rhetorical strategies with what students already know about discourse conventions (lemmas), while also enabling us to introduce new genre conventions (advance organizers in introductions) and processes (diagramming a proof to better understand and communicate it). In this way, drawing the logic of proofs as shown in the bottom half of the reasoning diagram has increased our integration of domains as we teach mathematical communication.

Computer Systems Diagrams: Making Tacit Reasoning Visible

Our research sought to make the discipline of computer systems' internalized reasoning patterns explicit. In our interviews with experts, we identified a small set of key concepts, such as system behaviors, properties, techniques, and metrics, which appeared in research papers under a variety of names. Additionally, when interviewing the authors of system papers, we heard about the context, actors, and environment that motivated or justified the systems, information that was minimized or unspoken in the published texts. Thus, our reasoning diagram needed to bridge the gap between expert publications and expert reasoning. For instance, computer systems papers typically report on the designs and techniques used to create systems that achieve desired metrics, but in class, students understand and design systems based on the use cases they fulfill. Students therefore must extract and sometimes infer the driving context and requirements of the systems they read about.

Our initial reasoning diagram in computer systems (Figure 7) is structured in two linked paths, showing that systems respond to, and are evaluated in the context of, use cases defined by user contexts and needs. Systems themselves are defined by the key concepts identified during the interview and design process, specifically behaviors; properties such as scalability, fault tolerance, etc.; and techniques such as modularity and abstraction, and metrics. We subsequently created a simplified version of this diagram for classroom use (Figure 8). This classroom diagram retained the dual-path structure and the key concepts, while other details and examples were integrated into other aspects of the curriculum.

The field of computer systems is introduced to undergraduates at MIT in an upper-level capstone class that covers multiple technical areas. Students read and discuss research papers in the field of system design; in teams, they also design their own theoretical system to solve a problem presented by the computer science teaching staff. The teams present this system in a preliminary and final design report, as well as an oral report between the two versions.

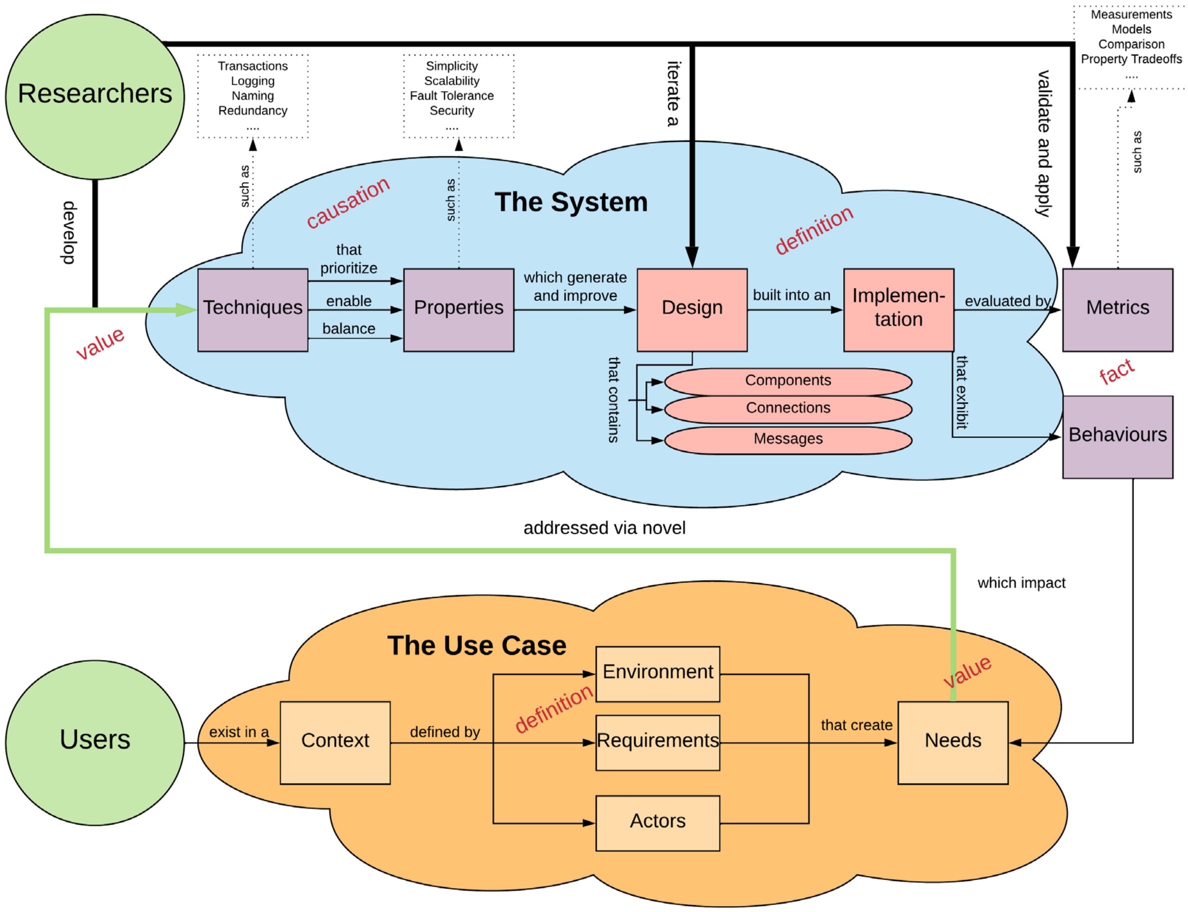

Figure 7: The Computer Systems Reasoning Diagram. The color coding indicates, generally, the context in which one considers a system—that of the users and use case (application, in yellow), and that of the system itself (in blue), with its design and implementation (in pink), and performance and evaluation (in purple). Researchers and users (both in green) are the starting points for the work, which moves iteratively between abstract design, implementation, and evaluation. The stases of each concept-concept relationship are marked in slanted red text. Examples of common techniques, properties, and metrics are offered in boxes outlined with dotted lines.

For most students, the readings assigned in class provide their first intensive experience engaging with advanced research reading skills and comprehension, and also their first engagement with complex computer systems. Because computer systems work is often published in conference proceedings and journals that don't offer a standard organization, the key concepts are not explicitly identified by the genre. The lack of explicit concept naming poses significant challenges when students need to transfer both communication and systems knowledge to their design, written, and presentation assignments.

The design project and reports contain many of the same conceptual elements as conference and journal papers (design properties, techniques, and evaluation) and require students to make explicit many components that remain implicit in those publications (detailing use cases, naming the categories and key concepts, etc.). In addition, these concepts align in similar argumentation patterns within student writing.

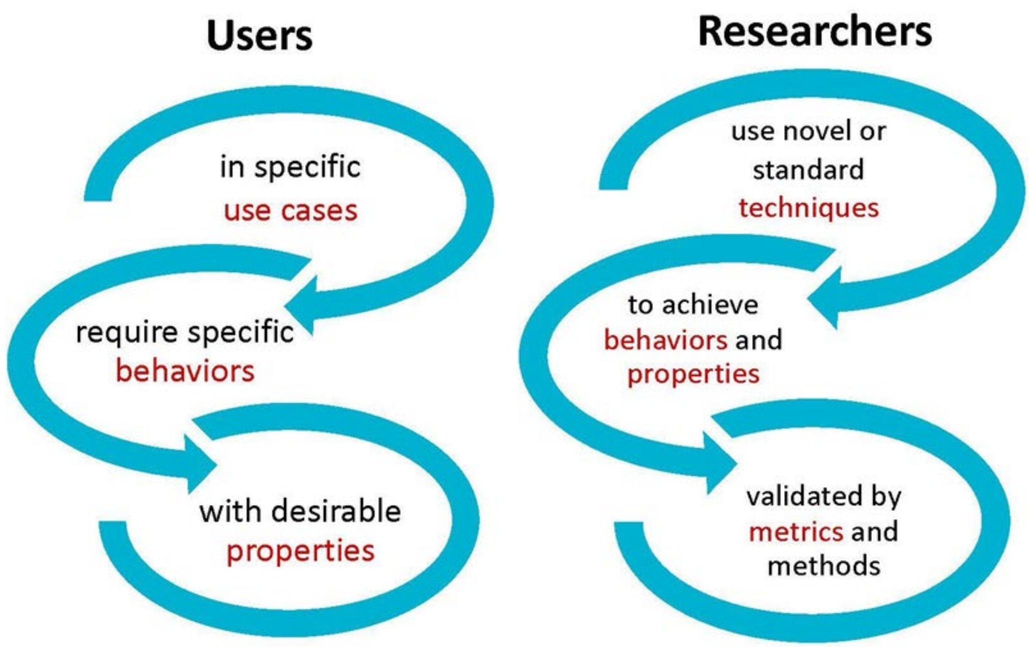

Figure 8: Classroom Diagrams for Computer Systems. This diagram consists of two reasoning paths that dominate how professionals in Computer Systems think about the discipline. The first illustrates how user interactions inform the design process. The second info

The reports also reflect many of the same points of open stases as the research papers; for example, value statements often revolve around prioritization of properties and the trade-offs in selecting one property over another, while claims of fact are often most applicable to the result sections. Thus, communication instructors use the reasoning diagrams to analogize types and structure of argumentation between the research papers read by students and the system design reports the students write.

To examine the utility of the adapted reasoning diagram in Figure 8, we surveyed students in this class about their use of reasoning diagrams to read papers, write papers, prepare oral presentations, and apply materials in class. The survey was IRB approved and student consent was required.

Out of a class of 373 students, 59 completed the final survey. While this represents only a small portion of enrolled students, the total number was sufficient to see key distinctions in many of the responses and represented the largest population to complete a survey about system diagrams to this point.

Table 1 shows that students primarily used the reasoning diagrams in tutorials (the sections of class where they worked with communication instructors and writing papers). A majority of students also reported using the reasoning diagram to prepare for oral presentations. A minority of students also used the reasoning diagrams in recitations (taught by computer science faculty) and in reading the published computer systems articles they covered in those classes.

Table 1: Number of computer systems students who reported using the reasoning diagram for specific class-related tasks. The sampling resulted in +/-8.55 confidence intervals at 95% confidence.

When did you use the reasoning diagram? (Check all that apply)	**Affirmative response rate**
Tutorial	83%
Recitation	39%
Writing Reports	76%
Reading System Papers	48%
While Preparing Presentations	63%

In Table 2, students favored using the reasoning diagrams in three sections: system overview, system components, and the system diagram. These areas most commonly discussed the core concepts of modules, use cases, and system properties, but also offered the most integrated descriptions of the student's system. We would have liked more application of the reasoning diagram in the evaluation section, as it also deals directly with use cases and evaluating the system performance and properties.

Table 2: Number of computer systems students who stated they used the reasoning diagram to write a specific section of the paper. The sampling resulted in +/-8.55 confidence intervals at 95% confidence.

When did you use the reasoning diagram? (Check all that apply)	**Affirmative response rate**
Tutorial	25%
Recitation	76%
Writing Reports	66%
Reading System Papers	17%
While Preparing Presentations	15%

When evaluating perceptions of student value (Table 3), we noted that students assigned the most value to using the diagrams to consider use cases. Students reported better than average value in using the diagrams to understand key concepts discussed in class and in connecting evaluations to specific techniques. The perceived utility of the diagram in connecting evaluation to specific properties and the reported lack of use of the reasoning diagram in writing the Evaluation section of the papers will require additional investigation.

Table 3: Average Likert results (1-Very Useful to 5--Not Useful) of questions designed to determine values of reasoning diagrams as viewed by computer systems students.

Would you find a version of the diagram with enough blank space to record the specific behaviors, properties, and metrics from articles useful as you read systems papers for class?	2.5
The diagram was useful in understanding the relationship between the system concepts that were discussed in recitation (e.g. connecting simplicity to modularity).	2.19
The diagram helped me to consider use cases as part of the design process.	1.69
The diagram helped me in understanding how evaluation connected to specific techniques and properties	2.06

Overall, student respondents indicated regular use of the reasoning diagrams in tutorials and writing of papers. The areas of the paper most focused on system design detail also were the areas where the students most used the reasoning, with the notable exception of the Evaluation sections. A majority of students also used the diagrams for preparing oral presentations, though only about 47% of respondents used the reasoning diagram for reading system papers. The results suggest that for the students responding to this survey, the reasoning diagram became a key part of in-class learning and post-class task completion and reasoning. Additionally, many students used the diagram to connect communication instruction from tutorial to computer systems instruction in recitation.

Conclusion

The reasoning diagram project reveals the complications involved in designing WAC/WID assignments that seek to offer opportunities for students to write authentic genres in their discipline, and in designing instruction that helps students to integrate the knowledge domains of subject matter, genre, discourse, rhetoric, and composing process. We've offered an approach that seeks to reveal tacit knowledge in each of these domains for students, and to show where and how they intersect. In multiple disciplines, our methodology has revealed interesting insights into how and why students struggle with composing authentic genres in classroom settings, as even small limitations on their access to expert knowledge and authentic activity systems can create confusion and disorganized or less effective texts. The reasoning diagrams have proven to be a useful tool for both instructors and students to identify these gaps and limitations, and students have been able to use them to resourcefully fill in those gaps on their own. In this sense, they function as a map that allows students to see what they need to know, but haven't been given full access to. In other cases, we as instructors have been able to help students work through these gaps more effectively.

Importantly, we want to stress that we don't view the reasoning diagrams as cementing knowledge about disciplines and genres, but as offering insights into current common patterns. Our view of both genres and disciplines is that they are dynamic and at most stabilized for now (Schryer, 1993), and any work with reasoning diagrams should help students understand their potential agency in performing disciplinary reasoning and genres, that the expectations of the discourse community for genre and discourse conventions are socially constructed over time, and that each individual study and text has the possibility of contributing to reshaping them. By mapping these reasoning relationships, we allow students a scaffold for learning to question and critique those relationships. As our revised MSE diagram shows, we also continue to revisit our visual representations as more tacit knowledge, or shifts in a field or genre, become apparent.

Much research has shown the processing of complex texts and conceptual material is enhanced through visualizations such as graphic organizers, concept maps, and knowledge maps (Schroeder et al., 2018). In future work we hope to analyze in more detail whether claims that have been made about those visualizations—that they reduce cognitive load by creating simplified noun-verb-noun propositions; make structural relationships more apparent (O'Donnell et al., 2002); and aid knowledge development by creating interactive structures that lead students to arrange and elaborate on meaning, leading to what has been called "elaborative interrogation" (Dunlosky et al., 2013)—are also relevant for reasoning diagrams.

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Contact Information

Suzanne Lane
Director, Writing, Rhetoric, and Professional Communication
Massachusetts Institute of Technology
Email: stlane@mit.edu

Atissa Banuazizi
Lecturer II
Writing, Rhetoric, and Professional Communication

Massachusetts Institute of Technology
Email: atissa@mit.edu

Malcah Effron
Lecturer II
Writing, Rhetoric, and Professional Communication
Massachusetts Institute of Technology
Email: meffron@mit.edu

Leslie Roldan
Lecturer II
Writing, Rhetoric, and Professional Communication
Massachusetts Institute of Technology
Email: lroldan@mit.edu

Susan Ruff
Lecturer II
Writing, Rhetoric, and Professional Communication
Massachusetts Institute of Technology
Email: ruff@mit.edu

Jessie Stickgold-Sarah
Lecturer II
Writing, Rhetoric, and Professional Communication
Massachusetts Institute of Technology
Email: jmss@mit.edu

Michael Trice
Lecturer II
Writing, Rhetoric, and Professional Communication
Massachusetts Institute of Technology
Email: mtrice@mit.edu

Andreas Karatsolis
Associate Director
Writing, Rhetoric, and Professional Communication
Massachusetts Institute of Technology
Email: karatsol@mit.edu

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