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Transfer and the Transformation of Writing Pedagogies in a Mathematics Course

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When it comes to developing a WAC/WID program, the final frontier may very well be the mathematics department. Writing in the discipline—in this case, proof writing—involves a highly specialized language of symbolic notation accessible only to those fluent in that language (Parker and Mattison 39). When working with mathematics faculty to develop writing-intensive courses, writing program administrators face a unique challenge: that mathematics writing is not "writing" in the conventional sense and so traditional best practices do not directly apply. In other words, invention techniques like freewriting and cubing, structured in their usual way, may not be as useful to mathematics writers as they are to writers in other disciplines—such as English, history, and sociology—that are not as positivistic. In terms of revision, given that proof writing is less subjective than most other kinds of academic writing, peer review runs the risk of becoming an empty exercise in which unknowledgeable students provide equally unknowledgeable students with faulty feedback. And if, instead, the task of providing feedback is left to the professor who corrects the errors in the proof, there is nothing left for the writer to "re-see" and to revise. Instead, the developing proof writer must learn to transfer the feedback from one proof and apply it to a different proof of a similar genre.

In this essay, two mathematics professors and a writing program administrator will explain how we addressed these valid discipline-specific concerns when we collaborated to re-envision an introduction to proofs course as writing-intensive. In his history of the WAC Movement, David R. Russell notes, "mathematics has been a leader" among "discipline-specific movements to incorporate writing in teaching" (320). Over the years, a spate of essays on writing and mathematics has appeared in journals in the fields of writing studies, mathematics, and mathematics education. Several of these essays focus on using writing to learn, arguing in different ways that writing helps students more effectively process and comprehend mathematical concepts (Shepard; Estes; Ganguli; Shibli; McCormick; Grossman et al.; Flesher; Bahls, "Math"). Others illustrate how mathematics instructors can implement WAC techniques like peer review (Fernsten; Gopen and Smith), journaling (Mower), and informal expressive writing assignments (Cherkas; Bahls "Metaphor"). Patrick Bahls has written extensively on the connection between mathematics writing and WAC techniques. His book, *Student Writing in the Quantitative Disciplines*, is meant "to help faculty in the quantitative disciplines see how writing figures prominently in the learning process" (ix). The book contains chapters on the writing process, assessing and responding to student learning, and formal and informal writing assignments. These scholars demonstrate how mathematics instructors can *transport* writing pedagogies into the mathematics classroom.

We will argue that to enhance learning, mathematics instructors must *transform* writing pedagogies to fit the genre of proof writing. We see this as a necessary extension of WAC/WID pedagogy. In his cogent historical analysis, Russell points out the "split" between general composition courses that deliberately sought to develop students' writing skills and specialized courses in the discipline that presumed "writing acquisition" was "unconscious" (28). As a result, the disciplines did not find it "necessary to examine, much less improve, the way students are initiated into their respective symbolic universes" (30). We not only consider the truly symbolic universe of mathematics writing, but we go even further, and consider how students are initiated into the discipline by examining how the writing process, particularly the invention and revision stages, maps onto an introductory proofs course. As Bahls observes, "the steps of [the writing] process may take different forms for different kinds of writing, and for different disciplines" (*Student* 25). As we have experienced, the writing process, with its roots in the humanities, is not entirely congruent with the proof-writing genre. We will show how we transformed the writing process, particularly the invention and revision stages, by 1.) implementing structured, genre-specific heuristics for the invention stage; 2.) modifying peer-review techniques to support the revision stage of proof writing; and 3.) instituting metacognitive journals with the goal of aiding "high-road" knowledge transfer.

An Introductory Proofs Course: Before and After WAC

The traditional model for teaching mathematics reflects the well-known maxim of the famous mathematician Paul Halmos: "the best way to learn [mathematics] is to do [mathematics]" (466). Many students learn to "do mathematics" by completing homework sets and taking short quizzes to check for major gaps in understanding. Since repeated practice is the key to mastering exams, students quickly learn that success results from "doing more problems." In the early 2000s, the mathematics faculty at Dickinson College decided that simply doing more problems was not enough; students needed direct instruction on how to write mathematical arguments. The faculty identified specific areas of deficiency that encompassed both higher and lower order writing skills. In terms of higher order skills, students had difficulty knowing when and how to apply the appropriate proof techniques, and identifying logical gaps or mistakes that render a proof invalid; in terms of lower order skills, students struggled with composing explanations that were concise and communicated clearly to a reader, naming the variables according to mathematical convention, and constructing complete and connected sentences (as opposed to bullet points or fragments). A representative example comes from the work of Alice, one of Jennifer's students, who attempted to prove across several drafts that the product of any two consecutive integers is even. The first sentence of her lengthier first draft reads:

> Suppose l and m are two consecutive integers such that $l=r$ and $m=q+1$.

This first version contains both higher and lower order problems. The higher issue is that Alice's definitions for l and m, namely that $l=r$ and $m=q+1$, do not support her assumption that l and m are consecutive and so her subsequent argument is illogical. The lower issue is that Alice's writing lacks concision because she uses more variables than is conventional; she need only use m. Making an attempt to correct her errors, Alice produces the following:

> Suppose l and m are two consecutive integers such that $l=n$ and $m=n+1$.

In her revision, Alice uses the correct definition of consecutive integers: n and $n+1$. However, she continues to use more variables than is conventional. In her final revision of this sentence, she addresses all of the concerns:

> Suppose *m and m+1* are two consecutive integers.

While this is a simple example, it is a common one that illustrates the kinds of higher and lower order thinking mathematics students must activate as they practice revision. Yet many students do not recognize the difference between higher and lower order concerns and so they do not know how to prioritize during the revision process.

Motivated to address these issues, the mathematics faculty decided to give proof writing more attention earlier in the curriculum. At the same time, there arose a college-wide initiative to develop writing-intensive courses in every major. The mathematics and computer science department responded by designating the introductory proofs course—in our curriculum discrete mathematics—as writing-intensive. Aiming to provide an effective gateway to the mathematics major, this course not only emphasizes discrete mathematics—including properties of numbers, sets, and functions—but also focuses on the art of writing mathematical arguments.

At first, mathematics faculty struggled to implement the criteria for writing-intensive courses in a way that made sense to them. The writing-intensive courses at our college combine WID and WAC learning goals: students learn the genres and conventions of the discipline (WID) and develop a functional writing process

(WAC). The mathematics and computer science department adopted Susanna Epps's *Discrete Mathematics and Applications,* a textbook whose rich resources and exercises on proofreading and the writing process address both goals. Complementing the student learning outcomes for the course, Epps's textbook covers the main genres of direct and indirect proofs. While faculty felt comfortable teaching disciplinary writing conventions, helping students develop a more functional writing process proved more problematic. Instructors incorporated an assortment of writing-related assignments and activities: for example, one created an in-house guide called "The Nuts and Bolts of Writing Mathematics," and others tried to implement revision exercises. Despite their efforts, instructors sensed the disconnection between writing and content instruction, and they struggled to develop a pedagogy that supported content and authentically incorporated the writing process as a means to developing stronger proof writers.

We began tackling the incongruence of proof writing with the process goals of writing-intensive courses in faculty development workshops. At Dickinson College, those teaching writing-intensive courses are invited to a half-day workshop entitled "Teaching the Writing-Intensive Course." This workshop draws faculty from across the disciplines and begins with a discussion of disciplinary genres and conventions before focusing on pedagogical skills like creating clear assignment prompts, designing an effective peer review, developing rubrics, and responding to writing assignments. After this workshop, faculty often elect to have follow-up consultations on course-specific concerns. Given the challenges that mathematics faculty were facing with authentically incorporating the writing process, we chose to meet and discuss how these techniques could be adapted to mathematical writing. This training and collaboration allowed us to prepare a course that fully integrated invention, peer review, revision, portfolios, and journals in a way that supported the development of proof writers. By taking full advantage of faculty development resources, we discovered new tools in the form of writing process pedagogy that truly helped our students *do* mathematics.

Transforming Invention Techniques

As we worked together to make the course writing-intensive, we grappled openly with a central question: is it helpful for mathematics writers to engage in the writing process—inventing, drafting, revising, and editing—when they are composing a mathematical proof? A mathematical proof "is a step-by-step logical or computational justification of a mathematical assertion, often drawing on prior proofs for its logical force" (Bahls, *Student* 22). Thus, prompts are not conducive to open-ended invention techniques like brainstorming or clustering. Consider the following prompt which is typical in an introductory proof-writing course:

Prove the following theorem: The sum of any two odd integers is even.

Since a proof is a written argument, to tackle this writing assignment, students must learn the content knowledge that would enable them to understand this statement, determine what makes the statement true, and then use logic to prove it. Traditionally, mathematics instructors would teach proof writing by demonstrating proofs—that is, composing perfectly formulated arguments on the board while their students watched in awe, marveling at the mystery. We wanted to figure out how to demystify proof writing by directly teaching disciplinary conventions that professional mathematicians have internalized. While the textbook explicitly covers logic, mathematical vocabulary, relevant theorems, and proof techniques, we wanted to teach the writing process and rhetorical situation. We began by focusing on the invention stage.

In *Student Writing in the Quantitative Disciplines*, Bahls recommends conventional invention techniques like freewriting, clustering, and cubing (24-29). While Bahls' techniques reflect the best practices of writing pedagogy, they are of limited use for proof writers because they do not take into account the highly specialized nature of the genre. For example, when describing freewriting, Bahls directs the writer to "gran[t] herself a fixed amount of time . . . during which she will write, nonstop, about a particular topic" (26). In mathematics writing, "scratch work" is the authentic equivalent of freewriting in which the writer works and reworks a shorthand version of a proof, including relevant terms, until she can visualize the end of the proof and the potential problem areas. Offering another traditional technique, Bahls defines cubing as a prewriting "tool designed to help writers examine a topic from every several [sic] different perspectives before writing about it more fully" (27). Bahls identifies "six faces of a cube": "describe it," "compare it," "associate it," "analyze it," "apply it," and "argue for or against it" (27). Conversely, we propose a new cube with discipline-specific prompts that scaffold the authentic invention process of mathematicians.

Table 1. Example Cube for Theorem: The sum of any two odd integers is even.

Invention Prompt	Pedagogy	Student Response
Summarize it.		
From a logical viewpoint, what does the theorem state?	Instructors teach symbolic logic and the logic of quantified statements during the first several weeks of class. Symbolic logic is the starting point for summarizing and categorizing statements.	Students should be able to summarize that the theorem is a statement about sums of any two odd integers. They should recognize that it is a universal statement and can be rewritten with logical quantifiers and variables. *For all integers m and n, if m and n are odd, then m+n is even.*
Unpack it.		
What are the key terms?	Instructors teach definitions so that students develop fluency in the underlying language of mathematics.	Students identify the key terms "integer," "odd," and "even." Students should rephrase those terms in mathematical language. For example: *Let n be an odd integer. Then n=2k+1 for some integer. k*
Delimit it.		
Given the logical form and key definitions, what is the appropriate starting and ending point for the proof?	Instructors model examples of how to begin and conclude a proof, often the most difficult skill for students. On assessments, instructors prompt students to "state the starting and ending point for this proof" to reinforce the importance of this step.	A student should know to start with the assumption that *m* and *n* are arbitrary odd integers and know the proof should conclude with *m+n* is an even integer.
Analyze it.		
Is the theorem true or false? Is the theorem's validity based on previous results?	After delimiting the statement, the beginning and end may not be straightforward to connect. Instructors demonstrate for the class how a mathematician develops counterexamples and explores the consequences of the veracity of a given statement—a skill that is especially important for the theorems that are not self-evident. This exploration is part of a trained mathematician's thought process and must be explicitly taught to beginning proof writers.	Students should realize that the theorem is true and its proof is straightforward. In this case, the definitions lend themselves to a sketch of the proof, easily verifying its validity.

Frame it.		
What is the best proof technique for the theorem?	Instructors teach the structure of each proof technique, when to use a specific one, and discipline-specific conventions (e.g., always do a direct proof, rather than indirect, when possible).	The student must consider the various proof techniques. Based on their scratch work, it should be apparent that a direct proof is possible and, therefore, preferable for this theorem.
Make it appeal to an audience.		
Who is your peer audience? Which steps used in the analysis are necessary and sufficient to convince them?	Instructors implement collaborative peer groups to make proof writers aware of audience. The students advance from the notion that a proof must be complete and omit no details to a more mathematically-sophisticated understanding of what is and is not common knowledge for an audience. By writing for an audience, clarity, conciseness, and exposition become integral to the proof, rather than afterthoughts.	The students should understand that the audience expects every step of this proof to be justified, as these steps constitute the argument itself.

The first column in the cube identifies questions we want proof writers to ask themselves in the invention stage. Rather than adopting open-ended and unspecific questions like "What can it be used for?" and "What are its inner workings?" (Bahls 27), this column identifies discipline-specific questions for proof writers. Assuming that instructors will directly teach the logic and mathematical content that writers need to invent proofs, the second column offers specific prompts to help the instructor guide the students as they address the question in the first column. The third column provides an example of a student response to the parity theorem mentioned above. While this theorem is a simple example, the questions are transferable to more complex theorems in advanced courses.

Transforming the Revision Process

Having re-imagined invention in a disciplinary context, we realized that revision as practiced in traditional writing courses would have to be adapted to fit a proof-writing course. In a traditional writing course, writers receive feedback from peers and/or the instructor and then use that feedback to produce a new and, ideally, improved version of the draft. In applying this model of revision to proof-writing assignments, we grappled with the argument of a colleague in mathematics who asserted that revision does not work in a proof-writing course because the instructor could not provide feedback on a proof without also revealing the answer to the proof. And once the instructor provided that feedback, there was no need for the student to do the problem again. Instead, the instructor would expect students to apply his feedback to the next proof, making "repetition," rather than revision, the goal. His comment raised several important questions for us. Would students better learn how to write proofs by repeating problem types, by revising one particular problem, or by practicing a combination of the two? Could peer reviewers give feedback—possibly even more effectively than professors—by virtue of the peer reviewers' novice positions? Or would unknowledgeable peers end up offering equally unknowledgeable peers faulty feedback? We resolved the repetition versus revision debate by having the students practice both—that is, revisit the same *genre* in homework problems and revise the same *problem* for final portfolios. On the one hand, when we assigned homework problems, we assumed the role of "expert correctors" in order to give students written feedback on the logic and rhetoric of their proofs. After receiving the comments, students would repeat the process, completing more problems until "practice made perfect." On the other hand, we instituted peer review because we saw the value of students' drafting, collaborating, and then revising the same proof as they constructed their portfolios. To that end, we assigned students to peer review groups at the beginning of the semester. When we posted daily homework problems, we also listed additional "portfolio problems" of the same type. Students selected and completed as many as three portfolio problems, which they submitted for daily peer review. At first, peer review was very difficult for them. Rather than unknowledgeable peers leading each other astray with bad advice, they would write superficial comments on each other's papers and then sit quietly together, engaging in very little discussion about their drafts. As a result, we revised our pedagogy and started teaching students how to engage in peer review. We would analyze sample proofs and apply tips gathered from multiple sources, including the rich guide on mathematical writing by Knuth, Larrabee and Roberts (4). As the students learned how to revise, they began focusing on a different group member's paper each day and their discussions began to evince more critical thinking.

We learned that peer review was effective, not just because it provided direct feedback for the writer but because it enabled the writer to re-see his own writing through that of his peers. Writers reported benefitting from conversations with their peers, as in the case of one student whose peer "helped give me ideas on how to better format one of my problems in my portfolio." This writer concluded, "As with all writings it's important to receive feedback to better the quality of the writings." More interestingly, several writers found peer review helpful because it created transfer experiences, enabling them to re-see their own work through the lens of their peers' work. One wrote, "There was an interesting peer reviewing incident where I and one of my peers both made the mistake of thinking that a statement was false and proceeding to provide identical counterexamples to disprove the statement. During the review, we both noticed each other's mistake and deduced where we went wrong." While this writer viewed the proof as a mathematical problem, using terms like "disprove the statement" and "mistake," two others viewed their proofs in writerly terms. One student wrote:

> Peer review was really helpful for me because it gave me an opportunity to see how other people approach the same problems. Not only was seeing other people's approach to the math portion helpful, especially with more complex proofs, but it was also helpful to see the *different ways people wrote*. There were some problems where I felt like *I just couldn't articulate* what I needed to in order to complete the proof. After reading over some of the solutions from my peer review group, however, I was able to figure out *what I was trying to say* and improve my own work. Being exposed to my *peers' writing styles* allowed me to regularly *reevaluate my own*, which has, I think, *made me a better proof writer*.

Another student explained:

> Among the many things I learned during peer review, the most valuable was learning *alternate ways to write our work*. Since so much of discrete mathematics relies on our *wording, clarity, and organization of problems*, it was extremely useful to see other's work and learn and share *better ways of expressing solutions*. (emphasis added)

Peer review showed these two writers "different ways people wrote" so that they could better "express" or "articulate" solutions. The second writer, in particular, uses writerly terms like "wording, clarity, and organization" to describe the proof-writing process. Both writers viewed revision as a writing, rather than a mathematical task, and they valued peer review because it enabled *transfer*: the ability to think about one's learning and to abstract from that learning principles that can be applied to another context (Salomon and Perkins). A fourth student states the transfer benefit most clearly: "It was also somewhat helpful to be able to look at someone else's proof and pickout mistakes because then I could transfer those kinds of objective thoughts when I looked at my own proofs" [sic]. In fact, when designing the writing-intensive component of this course, Sarah and Jennifer identified transfer as a major goal. In peer review, these four students practiced the "mindful abstracting of knowledge" from one context (their peers' papers) for use in another context (their own papers) (Salomon and Perkins 115). As such, rather than receiving direct critiques from peer reviewers, these writers engaged in the more complex task of critiquing a peer's draft, abstracting a mathematical principle, formulating their own feedback, and using it to revise their own writing. Far from misleading, peer review sharpened writers' critical reading and logical reasoning skills and helped them take ownership of their own work.

Teaching Metacognition and Aiding Transfer

These transfer moments were not just "happy accidents." Instead, writers were required to keep journals and regularly respond to metacognitive prompts created to aid the transfer of learning. In designing the journal assignment, we followed the advice of Anne Beaufort for "increasing the chances of transfer of learning" and taught learners "the practice of mindfulness or meta-cognition." Beaufort describes metacognition as "vigilant attentiveness to a series of high-level questions as one is in the process of writing" (Beaufort 152). To support knowledge transfer, students wrote at least one journal entry per week, summarizing a learning moment that they experienced. In addition, throughout the semester, they responded to specific prompts—what Beaufort calls high-level questions—that we created to help them reflect on the writing process and articulate abstract concepts regarding mathematical logic and methods of proof. The following is a sampling of our journal questions:

> Could you have found the answer by doing something different? What?
>
> Where else could you use this type of problem solving?
>
> What other strategies could you use to solve this problem?
>
> Write four steps for somebody else that will be solving this problem.
>
> What would you like to do better next time?
>
> What is one thing you have learned or changed because of peer-review feedback?
>
> Based on the feedback you have gotten on your homework, at what stage(s) in the proof-writing process can you make improvements?

Because we wanted this writing to be meaningful, we provided handouts on how to journal, and we intermittently collected the journals to make sure that students were being faithful scribes.

Given the time and effort students and instructors put into the creation of these journals, we wanted to know if writers benefitted from keeping a journal in a mathematics class or if the journal was nothing more than "busy work." Specifically, we combed the journals for evidence of transfer only to discover students reporting several varieties of transfer experiences related to both mathematical and writing contexts. In their oft-cited article on transfer mechanisms, Gavriel Salomon and David N. Perkins distinguish between forward-reaching and backward-reaching high-road transfer. According to Salomon and Perkins, in forward-reaching transfer, "the general formulation occurs initially and finds new application spontaneously later. One might say that during the initial learning it became set up for later spontaneous use . . ." (119). One student, we will call her Amy, anticipated forward-reaching transfer of mathematical principles when she observed of her discrete mathematics course: "This is sort of the beginning/basis for most future math classes; I hear that many of the coming courses are very much based on proofs, and having learned the basics and techniques of proof writing, this will clearly help in the future." While Amy understands that she will have to draw on her learning in other mathematics courses, Suhil explains how his knowledge of calculus from a previous semester helped him solve a proof by induction in discrete mathematics. In a detailed journal entry, Suhil explains his experience of backward-reaching high-road transfer:

> While working through proof 5.4.7 to create a strong induction proof for the portfolio (I had realized that I had none that I was really proud of), I had hit a wall. I couldn't find a way to get rid of a *k-1* subscript, and by this change from the recursive definition to the explicit definition of the equation, via substitution or any other clear technique. I had worked around the algebra for a while, working in circles for an extended period of time. Giving up on simply trying to solve it, I strategized.

Suhil experiments with some deductions and revisits his assumptions until he abstracts a principle from calculus, a course he had taken in an earlier semester. He continues, "Then, after looking into my algebra again, an idea from an integration by parts (my personal favorite integration technique) problem I had solved over a year ago came to me." After describing his mathematical reasoning in detail, he articulates the abstract principle: "The concept of needing to go back to the beginning in order to progress in some problems stuck with me. In this case, the 'a-ha' moment was realizing that I could work several steps backwards because of strong induction." Thus, Suhil experiences backward-reaching high-road transfer as he "formulates an abstraction guiding his . . . reaching back to past experience for relevant connections"—in this case, his abstractions from calculus enable him to revise his algebraic proof (Salomon and Perkins 119).

Other students, who spoke about the development of writing processes and skills, commented on how the lessons could be transferred not only to other mathematics courses but also to other disciplinary writing situations. Julie reflected on her struggle with "rational and irrational numbers." She learned that by

> building on the integer proofs by contradiction and understanding the theorem that stated the irrationality of square root of two, I could figure out where I needed to manipulate the math in order to reach a contradiction. This sort of consciousness about the problem is necessary for doing proofs

by induction, which require scratch work in order to figure out the more complicated conclusions necessary for my proof by strong induction.

Julie has awareness not only of the kind of "consciousness" she needs to write mathematically but also of the mathematical writing process, one that "require[s] scratch work." While Julie has developed process knowledge that will help her in subsequent mathematics courses, Adam imagines that what he learned about writing might be transferable to other disciplines: "This class may help with my essay writing as well in terms of planning, organization, and conciseness." Finally, Xiying anticipates the transfer of a general writing skill, concision, to other contexts: "Furthermore, the course has helped me improve upon basic writing skills, most notably my ability to be concise. In writing proofs, any extra wording often times detracts from the proof, thus one is forced to be concise." In figuring out how to eliminate extra wording from her writing, Xiying has developed an aspect of her writing style that will serve her well when she writes in other disciplines.

In telling the story of collaboration between two mathematics professors and a writing program director, we offer a writing pedagogy specifically tailored to writers of mathematics. At the same time, we also suggest how students who learn this specialized form of writing can be taught to think about the transfer of knowledge. The voices of writers captured in their journals speak strongly of their ability to imagine how their learning applies to different contexts both near and far—from subsequent courses in the mathematics curriculum to writing assignments in other disciplines.

Beyond the reflections students offered in their class journals, we want to know if students continued to transfer what they learned about the writing process to writing assignments in other classes—both within and outside of the mathematics department. To that end, we have fashioned a multipart assessment project. First, we will survey students about whether they continued to use writing process skills—like "scratch work," "cubing," peer review, and revision—when writing proofs for subsequent courses. Next, we will convene a focus group of students and ask them to share and discuss artifacts that exemplify these skills. A benefit of teaching at a small liberal arts college and having close relationships with students is that these kinds of assessment projects are feasible. Finally, focusing on mathematics majors and minors, we will compare the overall mathematics grade point averages of students in Jennifer's Discrete Mathematics course from 2008 with students in Jennifer and Sarah's WAC/WID transformed version of the course. By using a variety of assessment tools, we will determine whether or not students transferred the WAC/WID skills they learned in the course and improved their ability to write proofs.

Finally, we offer a lesson to WAC/WID directors about the importance of creating knowledge transfer opportunities in faculty development contexts. For WAC/WID directors, a major challenge when it comes to faculty development involves making disciplinary conventions explicit for faculty who do not routinely teach writing and who have internalized those conventions. Yet, in the words of Jennifer and Sarah, it was helpful when Noreen explained WAC/WID techniques and then helped them unpack the disciplinary-specific writing process that they had internalized, for in becoming conscious of their own writing processes, they learned to transfer those pedagogies, in an authentic way, to the mathematics writing culture. For Jennifer and Sarah, workshops were a good start, but one-on-one conversations that bridged the disciplinary language gap and examined the authenticity of proposed practices truly brought mathematics and writing pedagogy into congruence. Thus, through Beaufort's high-level questioning focused on the connection between disciplinary goals and writing practices, faculty can develop a deeper understanding of WAC/WID techniques, carefully transform those techniques, and then transfer them to their disciplines.

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