Essay

Writing-to-Learn in Undergraduate Science Education: A Community-Based, Conceptually Driven Approach

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Despite substantial evidence that writing can be an effective tool to promote student learning and engagement, writing-to-learn (WTL) practices are still not widely implemented in science, technology, engineering, and mathematics (STEM) disciplines, particularly at research universities. Two major deterrents to progress are the lack of a community of science faculty committed to undertaking and applying the necessary pedagogical research, and the absence of a conceptual framework to systematically guide study designs and integrate findings. To address these issues, we undertook an initiative, supported by the National Science Foundation and sponsored by the Reinvention Center, to build a community of WTL/STEM educators who would undertake a heuristic review of the literature and formulate a conceptual framework. In addition to generating a searchable database of empirically validated and promising WTL practices, our work lays the foundation for multi-university empirical studies of the effectiveness of WTL practices in advancing student learning and engagement.

INTRODUCTION

A significant challenge in science education is how to move students from thinking about science as a collection of facts to be memorized toward a deeper understanding of concepts and scientific ways of thinking. Within undergraduate science, technology, engineering, and mathematics (STEM) education, one approach that has garnered considerable attention is *learning-to-write*—strategies designed to improve student scientific writing (Moskovitz and Kellogg, 2011). In contrast, there has been a relative neglect of *writing-to-learn* (WTL)—using writing to improve student understanding of content, concepts, and the scientific method. Despite substantial evidence that writing can be an effective tool in student learning

and engagement (e.g., Poirrier, 1997; Bangert-Drowns *et al.*, 2004; Brewster and Klump, 2004; Thaiss and Zawacki, 2006; Carter *et al.*, 2007; Graham and Perin, 2007; National Survey of Student Engagement, 2008) and that WTL strategies can enhance knowledge acquisition and cognitive skill development in science disciplines (Rivard, 1994), WTL practices are still not widely implemented.

Rivard's insightful review of WTL in science disciplines identified several key issues that impede widespread acceptance and application of research findings. Since different types of writing tasks result in different kinds of learning, we need to determine the links between writing and both critical thinking and conceptual change. Furthermore, writing practices need to be studied in context, rather than in isolation, and research designs need to examine the interactions among specific learning objectives, personal characteristics (e.g., prior knowledge), models of instruction (coverage vs. conceptual understanding), and specific writing tasks. The underlying metacognitive processes necessary for learning specific types of knowledge (declarative, procedural, and conditional) also must be identified and targeted by corresponding WTL strategies. Since higher-order thinking involves restructuring knowledge, we need to determine what types of writing activities evoke this process of knowledge

transformation. Moreover, systematic, action-oriented research involving both qualitative and quantitative studies is needed to bridge the gap between researchers and practitioners. All these issues are still relevant today.

Given the promise of WTL and the specificity of Rivard's recommendations for further research, what accounts for the lack of progress in the intervening 18 yr, and what new approaches will be needed going forward? We argue that two of the major deterrents to progress are the lack of a community of science faculty committed to undertaking and applying the necessary research, and the absence of a conceptual framework to systematically guide study designs and integrate findings. A third deterrent is the continuing disconnect between research and practice, which prevents instructors from identifying and incorporating appropriate WTL interventions. In an effort to address these issues, we undertook an initiative, supported by the National Science Foundation (NSF) and sponsored by the Reinvention Center (a consortium of 65 U.S. research universities dedicated to the improvement of undergraduate education at research universities), to build a community of WTL/STEM educators who would undertake a heuristic review of the literature and formulate a conceptual framework to guide collaborative studies and educational practices.

A COMMUNITY-BASED APPROACH

Although we acknowledge that some writing pedagogies can be resource-intensive to implement, there are ample sources highlighting more efficient and equally effective strategies for responding to student writing (e.g., Spear, 1987; Thaiss, 1998; Elbow and Belanoff, 1999; Ferris, 2003; Russell, 2005; Volz and Saterbak, 2009; Bean and Weimer, 2011). Therefore, we began with the premise that STEM faculty reluctance to incorporate writing in their courses derives largely from a lack of awareness of the research on the effectiveness of WTL, since most published findings are in journals not regularly read by STEM faculty and the majority of studies use methods unfamiliar to most scientists. Rather than simply reviewing the literature yet again and delivering "take-home messages" to STEM faculty (a traditional approach), we hypothesized that a more effective approach would be to engage STEM faculty directly in identifying promising WTL practices that improve undergraduate learning in STEM education (a community-based approach).

Our first step in building community was to form a WTL working group made up of 12 well-known experts in STEM research and education (Table 1). Its members formulated the intellectual framework for the project and conducted a heuristic review of the literature that had four specific objectives: 1) create a searchable database of WTL resources for both educators and researchers; 2) identify empirically validated and promising WTL practices; 3) determine critical gaps in current knowledge; and 4) lay the foundation for multi-university empirical studies of the effectiveness of WTL practices in improving student learning in STEM disciplines.

The second step was to engage the STEM community in discussion of the most promising findings of the heuristic review and the implications for educational practice and research. Our method was to offer a workshop on WTL in STEM at the Reinvention Center 2010 Conference. The workshop was attended by 80 STEM faculty (the majority of whom were nominated by their universities' Vice Provosts) who collectively considered how effective and promising WTL approaches could be applied in courses they teach, and who developed recommendations for the next steps in the research process to advance understanding of effective uses of WTL practices in STEM education. The postworkshop evaluation survey responses ($n = 30$) indicated that 76% of participants believe WTL will be an effective new tool in strengthening their students' engagement; 90% expressed openness to experimenting with WTL practices and encouraging their colleagues to do so also; 79% expressed readiness to play a leadership role in the development of WTL at their institutions.

These findings attest to the value of the community-based approach. More specifically, by engaging the STEM community in both formulating the conceptual framework for the review of the literature and also in processing the findings with regard to the implications for both practice and subsequent research, we brought to bear a more diverse and inclusive perspective and yielded a set of recommendations more ready for implementation than the traditional approach of a single reviewer providing "take-home messages." Furthermore, the community-building process resulted in faculty not only expressing their readiness to participate in the development and implementation of WTL practices on their campuses but also undertaking planning of multi-university collaborative initiatives.

CONCEPTUAL FRAMEWORK: CONNECTING WTL, NEUROCOGNITIVE DEVELOPMENT, LEARNING, AND TEACHING

Several key findings identified in the seminal National Research Council report *How People Learn: Brain, Mind, Experience, and School* (National Research Council, 2000) have implications for educational practices: Learning changes the physical structure and functional organization of the brain and people construct new knowledge and understanding based on what they already know and believe. These prior beliefs and knowledge can either facilitate or interfere with new learning. A related finding is that neurocognitive development continues through adolescence into adulthood, as the brain, particularly the prefrontal cortex, goes through a remodeling process; these changes in the brain are paralleled by changes in the cognitive abilities supported by these regions, particularly the development of cognitive skills involved in executive functions, social cognition, and self-regulation (Blakemore and Chowdhury, 2006). This ongoing remodeling of the brain is the dynamic context in which undergraduate educational experiences are both impacted by and contribute to the development of higher-order cognitive processes and evaluative thinking.

Recent theory directs attention beyond the first-order cognitive processes that enable us to know about the world to the second-order metacognitive—"knowing about knowing"—processes that enable us to regulate cognitive, emotional, and motivational processes during learning (Kuhn, 1999). We now understand that successful learners are *self-regulated*, in that they employ a number of metacognitive processes while *making meaning* of information and their experiences. They elaborate on their existing knowledge, formulate relationships and

Table 1. WTL working group members

Greg Bothun, Professor of Physics, University of Oregon
David Hanson**,** Distinguished Service Professor of Chemistry, Stony Brook University
Wendy Katkin, Founding Director (Emeritus), The Reinvention Center
Jeffery Kovac, Professor of Chemistry, University of Tennessee
Lisa McNair, Assistant Professor of Engineering Education, Virginia Polytechnic Institute
Tamara Moore, Assistant Professor of Curriculum and Instruction and Co-Director of the STEM Education Center at the University of Minnesota, Minneapolis
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Arlene Russell, Senior Lecturer in Chemistry, University of California at Los Angeles
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make connections among items, develop self-explanations, and monitor their own understanding and comprehension. There has been a corresponding paradigm shift in education from a focus on the curriculum and the acquisition of content knowledge to developing the learners' metacognitive skills and learning strategies (Mayer, 1992) by incorporating modeling to make thinking visible and disciplinary practices overt, providing graduated supported practice ("scaffolding"), and encouraging reflection. Writing affords one of the most effective means for making thinking visible, and WTL practices can foster learning of both content and modes of thinking characteristic of disciplinary experts.

These advances in understanding about how people learn provide the salient conceptual framework for a common—and compelling—research agenda that we propose take the following general form: What is the role of [specific WTL practice] in improving [disciplinary-specific learning objective] through impacting [specific cognitive, metacognitive, motivational, and/or emotional process], as a function of [context variables, such as course level and class size; discipline; level, background, and goals of students; and subdiscipline, local, and institutional factors]? Having a common conceptual framework for research enables STEM educators to undertake studies appropriate to their interests and particular context, while simultaneously participating in collaborative studies within and across universities, such that their findings contribute to the broader delineation and mapping of effective WTL practices.

LITERATURE REVIEW

Building on Rivard's review, we focused our review on empirical studies published after 1994 in which writing strategies were designed to improve undergraduates' learning in STEM disciplines. We examined 324 journal articles, books, book sections, conference proceedings, and reports that were identified through searches in the Web of Science and ERIC databases or suggested by the working group. Of these sources, 203 specifically focused on WTL pedagogies within STEM disciplines at the college level. We filtered studies through the lens of learning theory and used our conceptual framework to organize and categorize findings by level of course, discipline, and learning objectives. Representative studies reporting empirically validated practices, as well as descriptive studies that are promising and warrant further

trials, were identified for each cell of the resulting matrix (Table 2). In addition, all studies were characterized by a number of additional key words to facilitate database searches (Table 3). The database is available at: http://bit.ly/fjudgo.

IMPLICATIONS FOR FUTURE RESEARCH DIRECTIONS

Our heuristic review found mostly descriptive case studies reporting on the effectiveness of particular WTL practices in improving students' learning. Building upon emerging efforts supported by the literature to move the research toward the analytical and experimental levels, we offer the following recommendations.

First, the role of writing in improving learning needs to be reconceptualized**.** Learning is no longer understood as simply "acquisition of knowledge," but as the construction of understanding and meaning as a result of social interaction. It is already well recognized that improving learning is no longer just a matter of strengthening associations and habits, but involves a change in understanding (Schoenfeld, 1999; Kuhn, 2005). The implications of writing assignments in STEM disciplines, therefore, should be reconceptualized to foster within students a shift from "knowledge telling" to "knowledge transforming" (Bereiter and Scardamalia, 1987).

Second, to establish the links between writing and both conceptual change and critical thinking within specific disciplines, learning objectives need to be operationally defined in terms of the disciplinary content, conceptual knowledge, or the "ways of thinking" that characterize experts in the field and must include the underlying processes proposed to mediate and moderate the effect of particular WTL practices on student learning (Table 2). Although there has been an enduring focus in higher education on developing critical thinking and reasoning as general skills across academic disciplines, research is increasingly providing support for the view that reasoning is situation or domain specific (Beyer *et al.*, 2007)

Third, studies must specifically seek to delineate the "mechanisms of effect" that is, the way in which a particular WTL practice brings about an improvement in student learning. How does writing "cause" learning to occur? Is it simply a matter of increasing time on task, or do students learn by applying cognitive and metacognitive strategies while writing? In addressing these questions, four interrelated systems have been demonstrated to affect learning

Table 2. Key citations from the WTL in STEM bibliographic database, organized by learning outcomes, discipline, and course level, that represent exemplary descriptive studies, empirically validated studies, and promising practices[a]

	Biology/Life Sciences	Chemistry	Engineering	Math/Computer Science/Statistics	Physics/Earth Sciences
Content knowledge	**Introductory:** Armstrong et al., 2008; Gerdeman et al., 2007; MacKay et al., 2005; Pelaez, 2002; Walvoord et al., 2008 **Advanced:** Nekvasil, 1998; Ryan and Campa, 2000	**Introductory:** Burke et al., 2006; Cooper, 1993; Margerum et al., 2007; Poock et al., 2007; Rosenthal, 1987; Shibley et al., 2001; Tilstra, 2001 **Advanced:** Lillig, 2008; May et al., 2010; Stoller et al., 2005; Whelan and Zare, 2003 **Capstone:** Schepmann and Hughes, 2006	**Introductory:** Hanson and Williams, 2008; **Advanced:** Ridgway and Young, 2005; Troy et al., 2004 **Capstone:** Berry and Carlson, 2010; Ostheimer and White, 2005	**Introductory:** Ganguli, 1994 **Advanced:** Barr, 1995 **Capstone:** Codespoti, 1994	**Introductory:** Allie et al., 2008; Rudd et al., 2009 **Advanced:** Blakeslee, 1997
Conceptual understanding	**Introductory:** Gerdeman et al., 2007; MacKay et al., 2005; Pelaez, 2002; Walvoord et al., 2008 **Advanced:** Nekvasil, 1998; Poronnik and Moni, 2006	**Introductory:** Burke et al., 2006; Coppola and Daniels, 1996; Poock et al., 2007 **Advanced:** Lillig, 2008; May et al., 2010; Reilly and Strickland, 2010	**Introductory:** Bommaraju, 2004; Scoles and Millan, 2005 **Capstone:** Berry and Carlson, 2010	**Introductory:** Brod et al., 2010 **Advanced:** Barr, 1995	**Introductory:** Cummings and Murphy, 2007; Goldberg and Bendall, 1995; Stewart and Ballard, 2010 **Advanced:** Blakeslee, 1997
Scientific method	**Introductory:** Gerdeman et al., 2007 **Advanced:** Clase et al., 2010	**Introductory:** McClure, 2009 **Advanced:** Alaimo et al., 2009; Lillig, 2008; May et al., 2010; Stoller et al., 2005	**Advanced:** Yalvac et al., 2007		**Advanced:** Blakeslee, 1997
Critical thinking	**Introductory:** MacKay et al., 2005; Pelaez, 2002 **Advanced:** Clase et al., 2010; Nekvasil, 1998; Ranelli and Nelson, 1998; Ryan and Campa, 2000 **Capstone:** Reynolds and Thompson, 2011	**Introductory:** Burke et al., 2006; Coppola and Daniels, 1996; Poock et al., 2007 **Advanced:** Alaimo et al., 2009; Kim et al., 2005; Lillig, 2008; May et al., 2010; Reilly and Strickland, 2010; Stoller et al., 2005 **Capstone:** Bressette and Breton, 2001; Schepmann and Hughes, 2006	**Introductory:** Newcomer et al., 2003 **Advanced:** Kim et al., 2005; Newcomer et al., 2003; Yalvac et al., 2007	**Introductory:** Fleron and Hotchkiss, 2001; Ganguli, 1994; Lerch et al., 2006 **Advanced:** Barr, 1995 **Capstone:** Fleron and Hotchkiss, 2001	**Introductory:** Guisasola et al., 2006; Kelly and Takao, 2002 **Advanced:** Blakeslee, 1997

(Continued)

Table 2. Continued

	Biology/Life Sciences	Chemistry	Engineering	Math/Computer Science/Statistics	Physics/Earth Sciences
Effective communication	**Advanced:** Clase et al., 2010; Poronnik and Moni, 2006; Ranelli and Nelson, 1998; Ryan and Campa, 2000	**Introductory:** Coppola and Daniels, 1996; Forbes and Davis, 2008; Kovac and Sherwood, 2001; McClure, 2009; Robinson, 2008; Tilstra, 2001 **Advanced:** Alaimo et al., 2009; Kim et al., 2005; Lillig, 2008; May et al., 2010; Robinson and Stoller, 2008; Sivey and Lee, 2008; Stoller et al., 2005 **Capstone:** Schepmann and Hughes, 2006; Wallner and Latosi-Sawin, 1999	**Introductory:** Hanson and Williams, 2008; Newcomer et al., 2003; Yoder and Sawyers, 2006 **Advanced:** Craig et al., 2008; Hecker, 1997; House et al., 2007; Kim et al., 2005; Newcomer et al., 2003; Troy et al., 2004 **Capstone:** Mirel and Olsen, 1998; Ostheimer and White, 2005; Wojahn et al., 2001	**Introductory:** Fleron and Hotchkiss, 2001 **Advanced:** Barr, 1995; Garvey, 2010 **Capstone:** Fleron and Hotchkiss, 2001	**Advanced:** Blakeslee, 1997
Metacognition	**Introductory:** Armstrong et al., 2008; MacKay et al., 2005 **Advanced:** Clase et al., 2010	**Introductory:** Jang, 2007	**Introductory:** Hanson and Williams, 2008 **Advanced:** Dahm et al., 2006; Thompson et al., 2005 **Capstone:** Mirel and Olsen, 1998	**Introductory:** Lerch et al., 2006	**Introductory:** Goldberg and Bendall, 1995; Jang, 2007; Klein, 2004
Professionalization	**Introductory:** Gerdeman et al., 2007 **Capstone:** Reynolds and Thompson, 2011	**Introductory:** Coppola and Daniels, 1996; Forbes and Davis, 2008; Robinson, 2008 **Advanced:** Alaimo et al., 2009; Lillig, 2008; May et al., 2010; Reilly and Strickland, 2010; Robinson, 2008; Robinson and Stoller, 2008; Stoller et al., 2005 **Capstone:** Wallner and Latosi-Sawin, 1999	**Introductory:** Newcomer et al., 2003 **Advanced:** Craig et al., 2008; Dahm et al., 2009; Dannels, 2000; Hecker, 1997; Newcomer et al., 2003; Troy et al., 2004 **Capstone:** Mirel and Olsen, 1998	**Introductory:** Fleron and Hotchkiss, 2001 **Capstone:** Fleron and Hotchkiss, 2001	**Advanced:** Blakeslee, 1997; Kelly et al., 2000

[a]Gaps in the table do not necessarily indicate an absence of studies, but rather indicate that we did not identify illustrative studies in those areas. The database of 324 journal articles, books, book sections, conference proceedings, and reports (located at http://bit.ly/fjudgo) can be searched by key words (Table 3). To search for multiple key words simultaneously, use the advanced search feature of the database and specify search fields as "anywhere."

Table 3. Key words used to organize and search WTL in STEM bibliography database

Discipline	Research level	Assignment type
• Biology and Life Sciences	• Descriptive	• CPR
• Chemistry	• Analytic	• Grant proposals
• Engineering	• Experimental	• Group project
• Math, Computer Science, and Statistics	• Meta-analysis	• In-class writing
• Physics and Earth Science	• Review	• Journal articles (includes journal-style papers)
Level	**Research methods**	• Journaling
• Introductory	• Assessment	• Lab report
• Advanced	• Analysis of assignments	• Literature review
• Capstone	• Comparison groups	• Multimedia project
	• Discourse analysis	• Multiple assignments
Learning outcomes	• Evaluations	• Op/ed (includes position papers)
• Content knowledge	• Exams	• Peer review
• Conceptual understanding	• Focus groups	• Reflective essay
• Scientific method	• Grounded analysis	• Research proposal
• Critical thinking	• Interviews	• Short paper
• Communication	• Qualitative	• Summary
• Metacognition	• Quantitative analysis	• Synthesis
• Professionalization (includes "disciplinary ways of knowing")	• Rubric	• Term paper
	• Survey	• Thesis
	• Think-aloud protocols	• Ungraded writing
		• Writing for publication

and therefore serve as potential intervention targets for WTL practices. Cognition involves the *skills* to encode and recall information: rehearsal, elaboration, organization, and comprehension-monitoring learning *strategies* (Weinstein and Mayer, 1985); and the *processes* of problem solving and critical thinking (Schraw *et al*., 2006). Metacognition involves planning, monitoring, and evaluating one's cognitive processes. Motivation involves those prior beliefs and attitudes that affect engagement with the task and the development and use of cognitive and metacognitive processes (Schraw *et al*., 2006). Emotion involves anxiety associated with performance, for example test anxiety or stereotype threat, and the notion of "troublesome knowledge," that is, when learning involves transformations in beliefs, commitments, and matters of identity (Meyer and Land, 2005). Although several studies have looked at the impact of metacognition in writing to promote learning gains (Thompson *et al*., 2005; Armstrong *et al*., 2008, Hanson and Williams, 2008), mechanisms of effect are rarely considered in WTL research in STEM (although Shah *et al*., 2009, is a notable example of how mechanisms could be studied).

Fourth, the extant evidence supports the effectiveness of two types of WTL assignments in particular for improving learning in STEM disciplines: 1) Assignments that focus critical reflection on one's epistemic beliefs regarding knowledge and understanding, problem solving, and application of knowledge (e.g., Bangert-Drowns *et al*., 2004, Lerch *et al*., 2006); and 2) assignments that engage the student in formulating a reasoned argument (e.g., Kelly *et al*., 2000; Bradley, 2001; Kelly and Takao, 2002; Lerner, 2007; Armstrong *et al*., 2008).

Fifth, we urge the adoption of a "hybrid" research paradigm that builds on the insights, methods and rubrics, and interpretative frameworks that characterize WTL scholarship in the humanities and social sciences, while promoting the hypothesis testing, controls, and experimental paradigm typical of the cognitive and natural sciences (Van Maanen, 1988; Lave and Wenger, 1991; Kirsch and Sullivan, 1992; Handelsman *et al*., 2004; Schell and Rawson, 2010). Such a "hybrid paradigm" would encourage multifactorial analytical and experimental-level studies that investigate and compare the impact of WTL practices on disciplinary-specific learning outcomes, using qualitative as well as quantitative assessment methods, as a function of hypothesized mediating and moderating variables, including emotional and motivational factors and learning context.

Finally, to address the gap between research and practice, we recommend that, in reporting on their work, researchers give attention to the kind of classroom situations and goals for which a specific WTL strategy is intended. Such information is necessary if practitioners are going to be confident in their choice and implementation of an intervention.

Rivard's conviction that "The area of writing to learn in science is ideal for developing collaborative projects in classroom inquiry" (p. 976) remains as true today as it was 18 yr ago. What is different is that the combination of the emerging community of WTL/ STEM educators, a learning-based conceptual framework, the database resulting from our heuristic review, and the adoption of the hybrid paradigm enables and empowers collaborative multi-university initiatives involving multidisciplinary teams of investigators to formulate and implement common protocols across multiple settings.

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