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Essay

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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 *e - - e*—strategies designed to improve student scientific writing (Moskovitz and Kellogg, 2011). In contrast, there has been a relative neglect of *- e* (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 *e .*, 2004; Brewster and Klump, 2004; Thaiss and Zawacki, 2006; Carter *e .*, 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 crit-

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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 fac-

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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 REVIE

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

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

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