Problem-Solving Pedagogies: Enhancing Undergraduate STEM Outcomes

Lynn C. Reimer, Amanda Nili, Tutrang Nguyen, Thurston Domina, and Mark Warschauer

University of California, Irvine

Author Note

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Correspondence concerning this proposal should be addressed to Lynn C. Reimer, School of Education, University of California, Education 3225, Irvine, CA 92697-5500. Email: lcreimer@uci.edu

Abstract

Science, technology, engineering, and math (STEM) fields require creativity to solve real-world problems. How do STEM students develop this expertise? Inclusion of problem solving in STEM courses is associated with positive student outcomes. However, research in the domain is limited to courses with student enrollments under 50 or single-discipline studies. Results reported here are taken from a larger study of promising instructional practices in entry-level STEM courses with enrollments of 200 or more. Researchers used institutional data and an observation protocol to identify problem solving in 40 sections of 8 introductory STEM courses. Results indicate that students exposed to problem solving during large lecture courses are more likely to progress to the next course and perform better in the next course.

Keywords: science, technology, engineering, mathematics, STEM, pedagogy, problem solving

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The first two years of undergraduate coursework are critical for persistence in STEM (Science, Technology, Engineering, and Mathematics). Initial student experiences with university STEM courses typically take place in large lecture courses, nicknamed "weeder courses." These lower-division courses are often organized into large lectures in which expert teachers transmit knowledge with minimal student interaction, preventing scientific discussion, analysis, and reflection (Baillie & Fitzgerald, 2010; National Academy of Engineering, 2005; Sheppard, Pellegrino, & Olds, 2008). Poor experiences in large lecture courses may contribute to the elevated attrition rate from STEM majors observed during the first two years of college (Mervis, 2010). Moreover, those who persist in STEM majors often have not developed the problem-solving expertise required for successful STEM careers (DeLuca & Lari, 2013). The lack of skilled graduates has significant implications for American global competitiveness. The development of problem-solving skills can be facilitated, even in large lecture halls, by both modeling problem solving and providing opportunities for the students to practice solving problems.

Problem solving is an approach to student learning involving case studies, constructivist learning, Discovery Learning, Problem-Based Learning, Project-Based Learning, and Inquiry-Based Learning. These approaches are thought to better equip students to pursue STEM careers by enhancing capacity to creatively resolve novel real-world problems. For the present study, observations of lectures and semi-structured interviews with STEM instructors identified courses that incorporate problem solving. Data on student academic performance, persistence in STEM major, and demographics were obtained from the university Office of Institutional Research

(OIR). Students exposed to problem solving in large lecture courses are more likely to progress and do better in the next course.

Literature Review

Demand for employees in STEM is projected to outpace demand for employees in other occupations (NSB, 2010). However, the number of STEM graduates from U.S. higher education is not keeping pace (Hurtado, Eagan, & Chang, 2010). Furthermore, STEM employers report that too many recent graduates are poorly prepared for the problem-solving tasks required in real-world applications (Lansiquot, Blake, Liou-Mark, & Dreyfuss, 2011; Vergara et al., 2009; NAE, 2005). For the past ten years, American STEM undergraduate programs have been a focal point of research to address this growing deficit. Large undergraduate introductory courses identified as gateway courses continue to favor pedagogies based on didactic lecture, often with course enrollments in the hundreds. Since a large majority of undergraduates enroll in these courses, identifying effective instructional practices could potentially decrease attrition from STEM majors and enhance problem-solving expertise (Mervis, 2010; NAE, 2005).

In 2011, two symposia brought together scientists and educators from across the United States to identify promising practices in undergraduate STEM education (Nielsen, 2011). Research on effective pedagogies was reported with implications discussed at length. Eleven promising practices were identified (p. 24). These practices were discussed in terms of ease of implementation and strength of outcomes. Problem solving was identified as one of the easiest to incorporate into instruction, with strong potential for enhanced student outcomes (p. 24).

Past Research

Studies abound on case studies, constructivist learning, Discovery Learning, Problem-Based Learning, Project-Based Learning, and Inquiry-Based Learning. Positive student outcomes, including motivation and course satisfaction (Colliver, 2000; Newman, 2005), test performance (Chaplin, 2009; Michael, 2006), content retention and recall (Gijbels, Dochy, Bossche, & Segers, 2005; Strobel & van Barneveld, 2009), and mastery of conceptual reasoning and problem solving skills (Antepohl & Herzig, 1999; Deslauriers, Schelew, & Wieman 2011; Dochy et al., 2003) have all been associated with problem solving.

Most of the extant research is focused on medicine and engineering (Antepohl & Herzig, 1999; Khousmi & Hadjou, 2005; Schuwirth, Verheggen, van der Vleuten, Boshuizen, & Dinant, 2001). Early adopters of non-traditional pedagogies abound in these fields. Schuwirth et al. (2001) explain that 20 healthcare students required to solve case studies elicited different strategies, such as re-reading of information, deliberation of facts, considering multiple causes and solutions, and thinking out loud (i.e., metacognition) compared to 20 general practitioners. The latter sample were quick to diagnose and systematically re-order information rather than considering content in the order it was delivered, leading to disregard for key facts. A study of pharmacology students found that students exposed to problem-solving pedagogies outperformed peers on measures of higher cognition involving reflection, synthesis, and analysis (Antepohl & Herzig, 1999). Moreover, the engineering department at a Canadian university chose to replace conventional, knowledge-acquisition instruction with “a learning methodology based on competence development, problem solving, and the realization of design projects,” (Khousmi & Hadjou, 2005, p. 5). In the end, students successfully completed competencies in each subject area rather than knowledge-based exams. These representative studies are discipline-specific, small enrollment, and upper division or graduate courses.

Fewer studies have been conducted in introductory courses. One study considered student performance in lecture-based versus a case study-based intervention course emphasized problem solving and discussion in lieu of certain lecture topics. Comparison of the two classes showed that exposure to case studies "improved student performance on exams throughout the semester and enhanced students' abilities to correctly answer application- and analysis-type questions" (Chaplin, 2009, p. 72). Like those studies in medicine and engineering, the student enrollment in this biology course was under 100. The relationship between problem-solving and student success in larger introductory courses remains open to study.

Problem Solving Defined

Incorporating problem solving into large lecture courses may improve undergraduate STEM education through acquired capacity to successfully attack problems. Mayer and Wittrock (2006) define problem solving as employing a strategy to move from a current state (problem) to a desired state (solution). The structure of the problem depends on the specificity and uniqueness of the solution (Bruning, Schraw, & Norby, 2011). Pretz, Naples, and Sternberg (2003) categorize problems as *ill-defined* or *well-defined*. When there is more than one acceptable solution, the solver could employ many different strategies to solve it; thus the problem is ill-defined. Smith and Ward (2012) describe solving this kind of problem as *divergent thinking:* "the search for many varied and imaginative possible problem solutions" (p. 465). In contrast, a well-defined problem has one correct solution and a guaranteed method for solving it (Bruning et al., 2011). This process has also been described as *convergent thinking:* "a type of problem solving or reasoning in which cognitive operations are intended to converge upon the single correct answer to a problem" (Smith & Ward, 2012, p. 465). STEM disciplines require the ability to solve both well-defined and ill-defined problems.

Effective innovations will need to be identified for large lecture courses. The American Association for University Women (AAUW) found that "students from historically disadvantaged groups such as African American and Hispanic students, both male and female, are less likely to have access to advanced courses in math and science in high school, which negatively affects their ability to enter and successfully complete STEM majors in college" (Hill, Corbett, & St. Rose, 2010, p. 5). The struggle is similar for those who are the first in their families to attend college (Davis, 2012). Research is needed to ascertain effective pedagogical reform of the widely agreed upon shortcomings of current undergraduate STEM education.

The present study explored the relation between problem solving and student achievement in large, introductory STEM courses at the University of California, Irvine (UCI). Two research questions framed the work. First, does problem solving in large introductory STEM courses positively impact students progressing to the next course? Second, is problem solving associated with increased academic achievement in the observed course and the subsequent course in a series?

Method

Setting

Our study employs systematic observations of instructional practice in large introductory STEM lecture courses from the Schools of Biological and Physical Sciences at UCI during the spring 2013, fall 2013, and winter 2014 quarters. UCI is a highly selective institution and these Schools are among the most recognized and fastest-growing units on campus. Together, they enroll 55 percent of UCI undergraduates and 95 percent of UCI undergraduates in STEM fields. Enrollment for these schools has increased by 20 percent between 2003 and 2012. Over the same period, UCI's student population has undergone substantial demographic changes. Currently, 55 percent of UCI students are first-generation college students and 30 percent are members of underrepresented minority groups (UCI, Office of Institutional Research). While more than 95 percent of UCI undergraduates earn a BA within six years, many students who begin as STEM majors transfer to other disciplines. After six years, fewer than half of incoming freshmen in the School of Physical Sciences earn a baccalaureate degree from that School, while retention rates of majors in Biological Sciences hover at approximately 60 percent (UCI Office of Institutional Research, 2013

By linking data from our observations of problem solving in large gateway lecture courses with student-level administration data, we take advantage of variation in instruction across courses to conduct a non-experimental, population-based evaluation of the extent to which problem solving promotes positive student outcomes during the first two years.

Sample and Procedure

We observed instruction in forty introductory STEM courses at UCI. Our study identified all courses in the School of Biological Sciences and Physical Sciences at UCI that were (a) prerequisites for other mandatory courses in one or more STEM major, (b) were offered in multiple sections during the course of the year, and (c) enrolled 200 or more students. Eight courses met these criteria: *Biological Sciences, From DNA to Organisms* (BioSci 93), *General Chemistry* (Chem 1A, Chem 1B, and Chem 1C), *Organic Chemistry* (Chem 51A and Chem 51B), *Single-Variate Calculus* (Math 2A), and *Classical Physics* (Phys 7C). During the year of the study, the university offered forty-two sections of these courses and forty sections participated in the study. Table 1 provides an overview of these courses.

[INSERT TABLE 1 HERE]

Trained research assistants observed one course session in the first three weeks and one course session in the last three weeks of regular instruction. For each observation, research assistants videotaped lectures and collected data on instructional strategies using a researcher-developed observation protocol (*Simple PRotocol for Observing Undergraduate Teaching;* SPROUT). SPROUT adapted content from three well-known observation protocols: U-Teach Observation Protocol (UTOP; Walkington et al., 2012); the Reformed Teaching Observation Protocol (RTOP; Sawada et al., 2002); and Teaching Dimensions Observation Protocol (TDOP; Hora & Ferrare, 2014). Observations include detailed field notes during the lecture, which were transferred subsequently to the observation protocol, and contained both dichotomous indicators and qualitative evidence. Two researchers overlapped on 20 percent of the course sessions with inter-rater reliability of Cohen's kappa = 0.80. Coding disagreements and ambiguities were discussed among the research team as they occurred during the data collection process.

Student administrative data were collected from the Office of Institutional Research (OIR). Our sample is diverse—58 percent are first-generation college students, 26 percent are members of underrepresented minority groups, and 56 percent are female. In addition to demographic and academic data, OIR provides course enrollments and grades (observed courses and subsequent terms), allowing us to track student progress toward STEM degrees. The sample consists of UCI freshmen and sophomores attending one or more focal (i.e., observed) courses. As few transfer students enroll in these introductory courses, they are excluded from analysis. The total sample includes 4,801 students. Students can enroll in more than one of the observed courses; thus a single student can provide more than one case and the analysis file includes 11,803 distinct observations.

Measures

The present study considers the relation between exposure to problem solving and: (a) student grades in the observed course (measured on a four-point scale, where an A is 4.0 and an F is 0.0), (b) student odds of enrolling in subsequent courses toward STEM degrees, and (c) student grades in subsequent STEM courses. Although many studies on instructional practices use concept inventories or examinations, these were not available in this observational cross-disciplinary study. Course syllabi indicate that grades in these classes were not curved to the mean, but rather on a straight point scale. Each of the observed courses serves as a prerequisite for another course in the same field. For example, students are required to successfully complete BioSci 93 in order to enroll in BioSci 94. Our subsequent enrollment outcome is a dichotomous measure of whether the student completed the subsequent course during the next academic term. Our third outcome is the student's grade in that subsequent course, conditional on enrollment and measured on a four-point scale.

Analyses

Course Progression

We consider the relation between problem solving and student achievement. We conduct logistic regression on the full sample to determine the relation between problem solving and course progression, using the model:

$$(1)\ Y_i = \beta_0 + \beta_1 Instruction + \beta_2 Covariates + \sum \beta_3 CourseTitle + \varepsilon$$

Y_i is the odds of taking the next course in the sequence. The parameter of interest in this model, *ProblemSolving*, estimates the extent to which exposure to problem solving in a given course influences a student's likelihood of progressing to the next course in the series. *ProblemSolving* is a dichotomous variable. A course either incorporates problem solving or does not. *Covariates* represents a vector of student-level demographic and academic controls. *CourseTitle* includes a matrix of course title fixed effects designed to control for aspects of content, instruction, and student behavior that do not vary across sections of the same course.

Grades in Observed and Subsequent Course

We consider the relation between problem solving and student achievement (grade in current course and grade in subsequent course) using ordinary least squares regressions and a student fixed-effects approach to provide an unbiased estimate, net of observed and unobserved student characteristics. [See Clotfelter, Ladd, and Vigdor (2007), and Xu, Hannaway, and Taylor (2011) for analyses using a very similar design in public high school settings.] These analyses take advantage of the fact that many students are enrolled in multiple courses that we observe. For example, typical first-year Biology majors at UCI might enroll in as many as four observed courses (i.e., Introductory Biology, General Chemistry, Organic Chemistry, and Calculus). These models take the following general form:

$$\beta_2 CourseTitle_j + \text{¿} \sum \beta_3 Covariates + \sum \beta_4 Student_i + \varepsilon$$
$$(2)\, Y_{ij} = \beta_0 + \beta_1 ProblemSolving + \sum \text{¿}$$

Student in this model is a matrix of student fixed effects, controlling for all characteristics of students that are fixed across courses, including observable characteristics such as student race, gender, economic and academic background, as well as invariant student characteristics such as intelligence and motivation. Because student characteristics such as race and family background do not vary across course observations, Model 2 excludes many of the student-level controls that our multivariate model includes. However, the model includes controls for student characteristics that do vary across courses, including indicators of whether students completed AP courses relevant to the focal course and whether they are repeating the course. The parameter of interest in this model, *ProblemSolving*, therefore estimates the extent to which exposure to problem solving in a given course influences a student's achievement in that course (along with subsequent course) when compared with other observed courses also taken by that student.

Model 2 provides more internally valid estimates of the causal effects of exposure to problem solving than Model 1. To be included in the student fixed effects model, students must take at least three observed courses ensuring that students take courses in more than one discipline. For example, rather than just Chem 1A and Chem 1B, a student taking three or more courses might also take BioSci 93. As a result, nearly half of the students who contribute to the Model 1 analyses contribute to the student fixed effects (Model 2) analyses. While the students in the fixed effects sample do not differ significantly from students in the whole sample on demographic characteristics, they do score slightly higher on several measures of prior achievement and include more STEM majors when compared with the full sample. However, we use the full sample in Model 1 to determine the odds of progressing to the next course, as we cannot run this analyses with the smaller student fixed effects model. An overview of the full sample can be found in Table 2 and the student fixed effects sample can be found in Table 3.

[INSERT TABLES 2 AND 3 HERE]

Results

Course Progression

The analyses reported in Table 3 consider the relation between problem solving and student odds of progressing to the next course in the STEM sequence. Since the outcome for this analysis is dichotomous (in which students who enroll in the next course in the instructional sequence take a value of 1 and students who do not take a value of 0), we are unable to estimate student fixed effects models considering the link between problem solving and student progression. However, Model 1 indicates that students who enroll in courses with problem solving are more likely to progress to the next course in the STEM sequence than peers in courses that do not incorporate problem solving (0.182, $p < 0.01$).

Grades in Observed and Subsequent Course

The analyses reported in Table 4 consider the relation between problem solving and grades. Although the student fixed effects model suggests that students achieve lower grades in courses that incorporate problem solving (-0.072, $p < 0.01$), perhaps the most powerful indicator of the extent to which problem solving influences students' acquisition and retention is the association between problem solving and grades in subsequent courses. The student fixed effects model suggests students achieve higher grades in the next course in the series (0.097, $p < 0.01$).

Discussion

This study aims to evaluate the effects of problem solving implemented at scale in large undergraduate introductory STEM courses (Nielsen, 2011). Small-scale studies and discipline-specific studies already suggest the potential for improving student outcomes by incorporating problem solving into courses. The current study confirms the benefit of problem solving in large, undergraduate STEM courses typical of major research universities. Although UCI is a single example and not generalizable to all undergraduate STEM universities, the university is fairly typical of at least one important segment of the American higher education system—the large research university.

Our findings suggest that the relation between problem solving and student achievement is significant, regardless of how problem solving is implemented. Our student fixed effects model suggests that students are more likely to progress to the next course and earn slightly higher grades in those courses when instructors utilized problem solving in the observed course. Although problem solving is associated with a negative effect on grades in the current course, it seems that long-term benefits are preferable for persistence in STEM majors. That the student fixed effects sample earn slightly higher grades in the next course is maybe less compelling than the fact that the full sample shows an increased likelihood of taking the next course. Further study is needed to ascertain whether students taking the first course as a breadth requirement, when exposed to problem solving, decide to pursue further study in STEM.

In interpreting these findings, it is worth noting that UCI is a selective institution. To enroll in introductory chemistry, biology, and mathematics courses, UCI students must either score above 600 on the mathematics portion of the SAT or complete a rigorous set of developmental math courses. While our sample of UCI introductory STEM students is ethnically and economically diverse, these students are likely to be more motivated and academically engaged than STEM students nationwide. These student characteristics may blunt the relation between instruction and student learning, insofar as UCI students' study skills and motivation can compensate for courses with ineffective instruction. If true, it is possible that problem solving and other promising instructional practices have a larger impact among heterogeneous students enrolled in STEM courses at community colleges and other less selective colleges and universities.

Strengths and Limitations

The National Academy of Sciences (NAS) and the National Research Council (NRC) have identified promising practices in STEM undergraduate education from a review of the research, much of which comes from evaluations of highly motivated and trained instructors in low-enrollment course settings or larger discipline-specific studies (Singer, Nielsen, & Schweingruber, 2012). Many of the recommended practices are difficult to implement in large lecture halls, yet universities are encouraging instructors to modify their instruction in ways that will increase student achievement.

The present study adapted previous research to gateway courses enrolling over 200 students in the interest of investigating whether incorporating problem solving, regardless of how it is implemented, may have broad positive effects. These gateway courses can make or break undergraduate persistence in STEM. Going forward, the present study will benefit from instructor and student interviews to elaborate on how problem solving is implemented.

We share our observation protocol and video recordings with instructors, allowing them to reflect on their own teaching. During interviews with instructors, many share their desire to improve their teaching, but are not always sure what to do. The results of this paper show that incorporating problem solving, required for successful STEM careers, is not only possible, but is also successful. This feedback encourages STEM instructors to provide scaffolding in large lecture halls by modeling problem solving and providing opportunities for students to practice solving problems during lecture.

The study is limited to a single research university, with a majority-minority population (49% Asian). Consequently, the sample is neither representative of research universities nor generalizable to American higher education. Additional observations are clearly needed. Future studies at other research universities with different student populations are necessary to address questions of reliability and validity. Additional longitudinal survey data following STEM graduates five years post-graduation will further validate the relation between problem solving and successful STEM careers.

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Appendix

Table 1

Description by Course of Students Enrolled in Focal Course and Subsequent Course

	Number of Course Sections	Number of Instructors	Number of Students	Percent Enrolled in Subsequent Course	Number of Students with Subsequent Course Grade
Biological Sciences 93	6	6	1,931	72.14%	1,393
Chemistry 1A	7	5	2,488	67.73%	1,685
Chemistry 1B	5	4	1,765	72.69%	1,283
Chemistry 1C	4	2	1,377	72.11%	993
Chemistry 51A	4	4	1,186	75.21%	892
Chemistry 51B	3	3	847	80.40%	681
Mathematics 2A	7	5	1,253	49.48%	620
Physics 7C	4	4	956	43.62%	417
Total	40	31	11,803	67.48%	7,964

Note: Many STEM students are not required to take the subsequent courses for Mathematics 2A and Physics 7C. 11,803 and 7,964 represent multiple observations of the same students. Total number of individual students for the full sample is 4,801 and for the student fixed effects sample is 2,382.

Table 2

Description of Full Sample

Variable	Total Observations	Total Students	Mean/ Percent	Standard Deviation	Minimum	Maximum
Math SAT#	11,494	4,610	0.00	1.00	-3.77	2.16
Verbal SAT#	11,494	4,610	0.00	1.00	-3.49	2.72
High school GPA#	11,786	4,789	0.00	1.00	-5.50	2.39
Focal Course AP	11,803	4,801	0.30	0.46	0.00	1.00
Male	11,791	4,792	0.42	0.49	0.00	1.00
Black	11,791	4,792	0.02	0.12	0.00	1.00
Hispanic	11,791	4,792	0.21	0.41	0.00	1.00
Non-resident	11,791	4,792	0.09	0.29	0.00	1.00
White	11,791	4,792	0.12	0.32	0.00	1.00
Other	11,803	4,801	0.03	0.18	0.00	1.00
Low income status	11,791	4,792	0.40	0.49	0.00	1.00
First generation college	11,791	4,792	0.55	0.50	0.00	1.00
Focal course in major	11,803	4,801	0.63	0.48	0.00	1.00
Fulltime student	11,803	4,801	1.00	0.07	0.00	1.00
Freshman	11,791	4,792	0.96	0.19	0.00	1.00
Repeating course	11,803	4,801	0.02	0.13	0.00	1.00

Note: Observations are repeated cases of students, as students are enrolled in one or more observed courses. #Denotes scores are standardized, and thus the mean is centered at zero. Asians were used as the reference group, as the university is considered a minority majority university (nearly 50% Asian). All others are dummy variables. In the "Mean/Percent" column, decimals for dummy variables show the percentage of students in that category.

Table 3

Description of Student Fixed Effects Sample: Students in Three or More Observed Courses

Variable	Observations	Students	Mean/ Percent	Standard Deviation	Minimum	Maximum
Math SAT#	8,216	2,353	0.02	0.96	-3.29	2.16
Verbal SAT#	8,216	2,353	0.05	0.97	-3.38	2.72
High school GPA#	8,297	2,379	0.10	0.90	-4.59	2.14
Focal Course AP	8,303	2,382	0.32	0.46	0.00	1.00
Male	8,297	2,379	0.42	0.49	0.00	1.00
Gender unknown	8,297	2,379	0.00	0.05	0.00	1.00
Black	8,297	2,379	0.02	0.12	0.00	1.00
Hispanic	8,297	2,379	0.20	0.40	0.00	1.00
Non-resident	8,297	2,379	0.08	0.26	0.00	1.00
White	8,297	2,379	0.12	0.32	0.00	1.00
Other	8,303	2,382	0.03	0.18	0.00	1.00
Low income status	8,297	2,379	0.41	0.49	0.00	1.00
First generation college	8,297	2,379	0.55	0.50	0.00	1.00
Focal course in major	8,303	2,382	0.71	0.45	0.00	1.00
Fulltime student	8,303	2,382	1.00	0.06	0.00	1.00
Freshman	8,297	2,379	0.99	0.12	0.00	1.00
Repeating course	8,303	2,382	0.02	0.14	0.00	1.00

Note: #Denotes scores are standardized, and thus the mean for this sub-sample is slightly above zero, compared with the full sample in Table 2. Asians were used as the reference group, as the university is considered a minority majority university (nearly 50% Asian). All others are dummy variables. In the "Mean/Percent" column, decimals for dummy variables show the percentage of students in that category.

Table 4

Effects of Problem Solving

	Bivariate	+ Student Level Controls	Student Fixed Effects
Outcome: Odds of progressing to next course			
	0.302***	0.182**	
	(0.066)	(0.068)	
N	11,494	11,493	--
Outcome: Grade in Observed course			
	0.012	-0.054	-0.072*
	(0.031)	(0.028)	(0.021)
N	11,348	11,347	4,744
Outcome: Grade in subsequent course			
	0.119***	0.051	0.097**
	(0.034)	(0.032)	(0.031)
N	7,762	7,762	4,744

Note: The items listed are individual components of the composite scales that were statistically significant. Student fixed effects include only students who took three or more of the observed courses. Standard errors in parentheses. Author's calculations. **p* < .05, ***p* < .01, ****p* < .001