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A Review of Learning-by-Teaching for Engineering Educators

ADAM R. CARBERRY
Arizona State University
Mesa, AZ
and

MATTHEW W. OHLAND
Purdue University
West Lafayette, IN

ABSTRACT

Learning-by-teaching is a pedagogical approach grossly underused in the education of engineers at all levels. The existing learning-by-teaching literature across all disciplines was reviewed with the intent of formally presenting this teaching method to engineering educators. The review defines learning-by-teaching, presents theoretical support for use, details the teaching process, and reports seminal work in a variety of contexts investigating the impacts on learning. The overall review is then discussed in terms of possible implications for engineering education.

Keywords: Learning-by-Teaching, Student-Centered Learning, Social Learning

INTRODUCTION

Teaching is the major tenet of education that imparts knowledge of or skill in a particular area. In the history of education, the practice of teaching has taken many forms and occurred in many different settings. Changes in teaching practices have mirrored human and technological development as well as societal needs. This is certainly true for engineering with a major shift in engineering education from practical application to engineering science around the time of World War II.

A continued evolution of teaching practices in engineering have been accompanied by the advent of engineering education research and a desire by countries to be competitive in science, technology, engineering, and mathematics. Knowledge about how people learn (Bransford, Brown, & Cocking, 2000), the learning styles of students (Felder, Felder, & Dietz, 2002; Felder & Silverman, 1988), pedagogies of engagement (Smith, Sheppard, Johnson, & Johnson, 2005), and success in college (Astin, 1993; Kuh, Kinzie, Schuh, & Witt, 2005; Pascarella & Terenzini, 1991; Pascarella & Terenzini, 2005) have suggested major renovations of the current practices; yet, the conventional view of teaching relative to learning has been unidirectional – experts responsible for teaching students. This traditional perspective is in direct contradiction to the ancient philosophy that "by teaching we are learning" and the famous Joseph Joubert (French Philosopher, 1754-1824) quote that "to teach is to learn twice". Initiatives started in the 1980's to implement active (Bonwell & Eison, 1991) and experiential learning (Kolb, 1984) have allowed student-centered approaches to become a focal point of engineering education reform (Prince, 2004); however, learning-by-teaching has seen sparse discussion in the literature.

Placing the student in the role of teacher permits the student to benefit from the activities implicit in teaching and simultaneously allows the teacher to play the more effective role of coach or guide. As such, the roles of teacher and learner are blurred to allow both stakeholders to succeed in their given task. Successful implementation of this pedagogy has been seen at the K-12 level in the Montessori schools (Lillard & Else-Quest, 2006) and the Lernen durch Lehren programs throughout Germany (Martin, 1989).

The following review examines the underlying principles of learning-by-teaching with the purpose of explicit introduction and increased awareness of this effective pedagogical approach to engineering educators. First, an analysis of the activities involved in the teaching process will be used to describe the mechanisms that elicit learning. Next, a discussion of associated theoretical underpinnings is presented to establish a support framework for offering students a teaching practicum. Finally, a description of various learning-by-teaching approaches – peer tutoring, teaching assistantships, cooperative learning, clinical experiences, teachable agents, and K-12 outreach – and a description of the research surrounding these approaches will demonstrate how learning-by-teaching has been used and what the potential benefits are in engineering education.

THE TEACHING PROCESS

The activities required of a teacher in practice have concomitant cognitive benefits for that teacher. These activities include preparation, presentation, and assessment facilitated by review, reformulation, organization, reflection and observation (Bargh & Schul, 1980; Gartner, Kohler, & Riessman, 1971; Martin, 1985; Okita & Schwartz, 2006).

Preparation

Teaching requires a basic understanding of the material to be taught and a plan for conveying the learning objectives. To ensure understanding before presentation, teachers need to understand the learning context and often learn by reviewing important explanatory structures in the domain (Artzt & Armour-Thomas, 1999; Bransford, Brown, & Cocking, 2000). *Learning-by-reviewing* includes many instances when a teacher works with the material while preparing to teach (Gartner et al., 1971). There are two qualitative differences when reviewing for a teaching role rather than studying materials for personal gain (Bargh & Schul, 1980; Hufnagel, 1984). The first difference is a shift in the reviewer's content-specific gain from learning for a test to learning for the capability of explaining to another. Reviewing for the purposes of teaching shifts learning away from memorizing the facts with no context. The second qualitative difference is a teacher's use of reformulation. *Learning-by-reformulation* leads to a deeper grasp and understanding of the material through organization and the basic seeking out of structures (Gartner et al., 1971). Organization encourages the teacher to code the content in a meaningful way that associates the material with what is already known.

Preparation for teaching places a powerful responsibility on the teacher to succeed so that his or her students do not fail. Metacognitive motivation concerning someone else's wellbeing intrinsically drives teachers to remedy their misunderstandings in case a student needs further clarification (Lambiotte et al., 1987). Teachers also prefer to not be embarrassed by not knowing the answer. Such motivation encourages the teacher to pay more attention to the material to be learned, enhancing cognitive processing and increasing attention for the task (Annis, 1983; Benware & Deci, 1984).

Presentation

Presenting to an audience contains the additional benefit of learning communication skills; it also holds the possible drawback of anxiety induced by an "audience effect" (Zajonc, 1966). The benefit typically outweighs the fear because it allows the student to verbalize (Chi, De Leeuw, Chiu, & Lavancher, 1994). Verbalization allows students to talk about content in an active and meaningful way rather than passively contemplating what is being lectured to them. The teacher is also afforded the opportunity to mentally record reactions of the audience for future reflection.

Assessment

The final activity implicit in teaching is student assessment. Assessing student achievement allows the teacher to see how his or her students use what they have learned and whether they are truly grasping the material (Chi et al., 2001; Graesser, Person, & Magliano, 1995; Palinscar & Brown, 1984). Assessment is accompanied by an opportunity for the teacher to observe and reflect. Together these activities supply opportunities to analyze personal performance and gain insight into personal understanding of the material. Reflection can be triggered by internal and external cues. Internal cues occur naturally when the teacher presents and discovers a personal deficiency in understanding. External cues through observation are supplied to the teacher through observed student reactions including non-verbal reactions, student questions, and student assessments. Non-verbal reactions allow the teacher to receive instant feedback on their teaching. Student questions test the teacher's understanding and prompt non-scripted verbalization promoting achievement (Webb, 1991, 1992). A question also indicates student confusion, which makes the teacher cognizant of possible conceptual gaps and discrepancies that may exist for the student and the teacher (Bargh & Schul, 1980; Lin, Schwartz, & Hatano, 2005). Reflection on student questions leads to reorganization and clarification of the material improving their own fundamental understanding and improving future learning sessions (Chi, Silver, Jeong, Yamauchi, & Hausmann, 2001; Lin et al., 2005). When someone has an understanding of what they are observing, observation can trigger reflection not produced when analyzing student questions or looking at student work (Okita & Schwartz, 2006).

Summary

When these activities are taken together and supplemented with review, reformulation, organization, reflection, and observation, they form the process of teaching. In Figure 1, we have combined the steps identified in the literature into a flowchart to visually represent the process that students experience when given an opportunity to teach. In creating this model, we by no means intend to suggest that these are the only processes that can occur. We do however believe that a well-structured teaching experience formed around this model can induce this cyclical process.

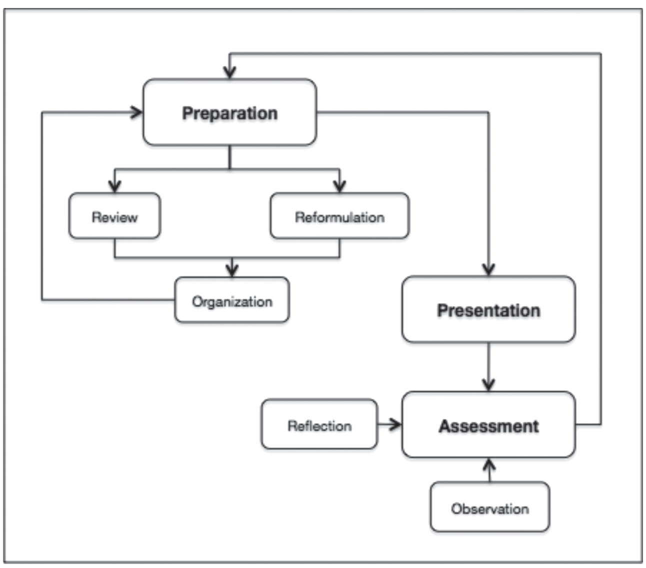

Figure 1. The teaching process.

LITERATURE REVIEW

Many different learning-by-teaching approaches have been designed and used at many levels of education across all disciplines. These approaches include:

- student-led lecture, peer tutoring – using advanced students to assist those having difficulty (Goodlad & Hirst, 1989),
- teaching assistantships – graduate student assistants used to supplement large collegiate classes and aid in the graduate students' mastery of the field (Moust & Schmidt, 1994; Nyquist, Abbott, Wulff, & Sprague, 1991),
- cooperative learning – promoting learning together through positive interdependence, face-to-face interactions, individual and group accountability, interpersonal and small-group skills, and group processing (Johnson & Johnson, 1983; Johnson, Johnson, & Smith, 1991; Slavin, 1983, 1995; Smith, 1996),
- pre-service teacher clinical experiences – teaching internships used to apply and connect knowledge, skills, and attitudes developed in class (Titley, 1984),
- teachable agents – intelligent tutoring systems designed to virtually elicit learning-by-teaching (Brophy, Biswas, Katzlberger, Bransford, & Schwartz, 2000), and
- K-12 outreach – civic opportunities to teach K-12 teachers and students.

Each approach is based on the principle that teaching experiences positively affect learning, although the different approaches do not always explicitly use each of the processes shown in Figure 1. The studies selected for inclusion in this paper will be used to explain the overarching effectiveness of learning-by-teaching approaches.

Bargh and Schul (1980) conducted an analysis on the effects of *expecting to teach* toward student cognitive gain. Two groups of undergraduates in an introductory psychology course were formed in a closed experiment: one expecting to teach a single student and the other preparing to be examined about two written passages. The group expecting to teach did not actually teach, but post-test performance scores identified the teaching expectancy group (Mean, M = 0.649) to have significantly outperformed the group expecting to be examined (M = 0.569). Subsequently, a second experiment was conducted using both a verbal and problem-solving task to analyze the effects of practice on performance. Undergraduate subjects were split into three groups: work alone, verbalize thoughts and ideas while working alone, and taught another while working on the task. Verbalization failed to result in a better performance for either task. Bargh and Schul hypothesized that these results were an effect of student teaching anticipation, rather than the actual act of teaching.

Annis (1983) extended the analysis by measuring the achievement of undergraduates (sophomores) on content-specific and generalized cognitive gains for five groups: *read* – reading for the purpose of being examined*; read to teach* – reading with the intent to prepare to teach another student, but with no actual teaching involved*; read and teach* – reading to prepare and actually teach a tutee*; be taught* – taught with no background information*;* and *read and be taught* – taught after previously reading the excerpt. The analysis looked at the effects of teaching expectancy, exposure to teaching, and teaching experience within the context of world history. Analysis showed that those students in the *read and teach* (M = 6.31) group significantly outperformed all other groups in knowledge (*read*, M = 4.0; *read to teach*, M = 4.81; *be taught*, M = 3.35; *read and be taught*, M = 5.08). Also noteworthy was the result that the *read* and *be taught* groups significantly outscored the *be taught and read* group and the *read to teach* students significantly outscored the students who were in the *be taught* group. Annis' results clarify the work of Bargh & Schul by showing that actively being engaged in teaching, rather than being passively exposed to material is the most beneficial avenue for learning within a learning-by-teaching environment.

A contradictory experiment by Ehly, Keith, and Bratton (1987) analyzed the post-test scores for five groups (*Teach I*, *Teach II*, *Study*, *Learn*, and *Control)* of high school students in a psychology class with an embedded learning-by-teaching experience. Both the *Teach I & II* groups were given lesson content in advance. The *Teach II* group was identical to Bargh and Schul's group of students expecting to teach, but with no actual teaching opportunity; while the *Teach I* group represented students both expecting to teach and who actually had the opportunity to teach. Students who learned from the *Teach I* group formed the *Learn* group. The final two groups, the *Study* and *Control* groups, represented students who expected to be examined and students with zero exposure to the material before being tested, respectively. While analyzing the effects of teaching expectancy and the differences between studying to tutor and studying to take a test, they concluded that expectancy did not sufficiently produce mastery of the content; students who actually taught (*Teach I,* (M = 25.63) were outscored by students expecting to teach (*Teach II,* M = 19.62) and students who were taught (Learn, M = 25.67) when means were adjusted for variable study times. The researchers recognized an undeniable impact of expectancy, but concluded that knowledge of content was more influential than simple exposure to materials in a teaching role. Nonetheless, an actual teaching experience did have a positive impact.

Lambiotte *et al.* (1987) clarified this discrepancy by analyzing different interactions between undergraduate psychology students in a one-on-one student-taught lesson. Four groups were analyzed: *cooperative teaching in the teaching role*, *cooperative teaching in the learning role*, *cooperative learning*, and *cooperative microteaching*. These four conditions varied in what each partner read, taught, and learned about two contexts: sailboat materials and cardiac monitors. They concluded that preparing for and teaching information to a naïve learner resulted in the highest gross overall scores on recall even when each group was exposed to the same materials (*cooperative teaching in* *the teaching role*, M = 8.69; *cooperative teaching in the learning role*, M = 5.46; *cooperative learning*, M = 3.95; *cooperative microteaching*, M = 4.80). Lambiotte *et al*. suggest that it is differing amounts of effort, demand characteristics, social factors, and variable metacognitive activity that account for these differences rather than exposure to the materials.

Benware & Deci's (1984) analysis of two undergraduate (first-years) groups, *reading to learn for a test (control)* and *reading to learn to teach a peer (experimental),* took the investigation one step further by assessing how teaching the topic of brain functioning to another student effected conceptual understanding verse rote learning. They found that both groups performed equally well on rote learning (M = 16.24; M = 18.21), but the *learn to teach* group (M = 18.84) outperformed the *learn for a test* group (M = 10.76) on conceptual understanding. In addition, Benware & Deci identified that teaching facilitated significantly high levels of interest (M = 4.43; M = 7.13) and enjoyment (M = 4.67; M = 7.00) brought about by a sense of competence and self-determination. This result goes beyond cognitive gain to suggest that learning for the purposes of teaching intrinsically motivates students more than learning for the purpose of being examined. Renkl (1995) contrarily found that students studying worked-out examples displayed significantly lower levels of intrinsic motivation (M = 3.27; M = 2.60) when the task was in preparation to teach; however, the study's results were found to be biased based on low levels of competence and self-determinism.

Renkl's study of education undergraduates' work with probability additionally found that students preparing to teach performed the task with somewhat more anxiety (M = 2.34; M = 2.72). Renkl's identification of high levels of anxiety were paralleled in a study by Ross & DiVesta (1976) on undergraduate students in an introductory educational psychology course. Students were asked to read a passage about a fictitious primitive tribe. A comparison of anxiety brought on when students verbalized their answers (M = 31.81) and when they observed someone else verbalizing (M = 21.19) resulted in significantly increased levels of anxiety when students were engaged in verbalization activities. The study concludes that teaching expectancy can foster learning, but can be hampered by the anxiety of having to speak in front of a group.

The overall results of these studies suggest that exposure to teaching opportunities can afford students both cognitive and emotional benefits not seen when passively taught. The one caveat is that these benefits may be hampered by high anxiety induced by an audience effect.

THEORETICAL FRAMEWORK

Freire (1987) suggests that teachers must become learners and learners must become teachers if learners are to gradually understand what they did not yet know. The proposal that students should experience the role of the teacher is based on the assumption that teaching produces a richer experience than learning by oneself, encourages individuals to make their thoughts explicit, and supplies a context for building arguments differently from those one would build independently (Kafai & Harel, 1991).

These assumptions can be theoretically supported in three ways: 1) linking practice to theory, 2) linking theory to practice, and 3) reflection. The traditional theory is that a teaching experience grants students with a situation to link theory with practice within a regularly structured and supervised situation. The underlying argument is that students learn by first grasping the theory before applying it to practice in the form of teaching. The second theory argues that the role of a teaching practicum is to raise problems and issues used to trigger the investigation of related theory and pedagogical knowledge (Kolb, 1984). This argument reverses the role of theory and practice so that learning is achieved by doing. The first and second theories both describe opportunities that elicit the three assumptions through group learning and shared knowledge. The third alternative theory argues that the crucial factor is the opportunity to reflect on or to examine experience in the light of the individual's current knowledge and understanding (Boud, Keogh, & Walker, 1985; Schon, 1990). The focus of this argument is on what enables learners to turn experience into learning for the purpose of gaining maximum benefit from the situation. The assumptions can still be made because teaching reflection provides a group experience regarding thoughts and ideas. Each of these theories shares the underlying theme that teaching has the capacity to be an effective tool for learning.

The support for learning-by-teaching implementation is heavily based on implicit and direct social interactions. Hartman (1990) theorized that social interactions induced by teaching can produce valuable cognitive benefits toward personal development that are not seen through any other form of learning. Social learning has the potential to provide a theoretical basis for learning-by-teaching, yet the social learning literature reveals that no one theory has the full capacity to explain why it is that learning-by-teaching is advantageous. However, a combination of cognitive, behavioral, and environmental attributes of social-learning-based theories can be used to produce a theoretical framework for learning-by-teaching.

Such a learning-by-teaching theoretical framework starts with an individual's personal development. Vygotsky's Social Development Theory (1978) is driven by the effects of social interactions on cognitive structures. According to Vygotsky, full cognitive development hinges on social interactions. Social exchanges and conflicts allow the learner to observe and model behaviors, attitudes, and emotional reactions they may not normally perform on their own. These observations encourage the internalization of social and cognitive processes leading to the development of higher-order functions difficult to achieve through self-exploration alone. This concept is illustrated clearly in Vygotsky's Zone of Proximal Development (ZPD). The ZPD is a shifting range that identifies an individual's real-time array of capabilities. The lower bound is defined by an individual's ability to solve a problem alone, while the upper bound is defined by the ability to solve a problem with help from an "expert". Social interactions and the advancement of individual ability are dictated by shifts in ZPD through experiences with experts and peers.

Learning-by-teaching suggests that the upper bound of an expert's ZPD can be shifted when the expert interacts with a novice. Implications of this theory on peer learning have been discussed (Hogan & Tudge, 1999), but to date, no research has been conducted specifically looking at how, if at all, an expert's ZPD changes through such interactions; the focus is generally on changes to the ZPD of the novice. The upper bound for the expert could be defined by the ability to reason a problem for the purposes of explaining them to a novice. In situations where the teacher's upper bound is challenged by a question, the teacher and student essentially switch roles. The expert does not necessarily become the novice per se, but the novice's question causes the expert to consider the content in a way they have never thought to have previously. This causes the teacher to question what they know about the domain temporarily making them the "novice". This temporary moment puts the expert in a state of disequilibrium shifting the upper bound of his or her ZPD until they accommodate and assimilate a new understanding.

Social learning extends beyond simply working with others and establishing differing points of view. It incorporates cognitive, behavioral, and environmental influences that affect both teaching and learning (Bandura, 1977). These influences are the basis for why it can be assumed that learning socially and concomitantly learning-by-teaching: 1) sometimes produces a richer experience than learning by oneself, 2) encourages individuals to make their thoughts explicit rather than implicit, and 3) supplies a context for building arguments differently from those one would build independently (Kafai & Harel, 1991). Competencies are developed through mastery learning elicited through imitation, observation, and modeling of behaviors, attitudes, and emotional reactions. For example, a teaching practicum provides a mastery experience driven by cognitive apprenticeship (Collins, Brown, & Holum, 1991), which allows the teacher to provide a visible model to be observed and imitated by the learners. When the teacher prompts the students to become the model, they are given an opportunity to display what they have learned using the activities implicit in teaching. Learning by this fashion becomes situated, visible, and a function of the activity, context, and culture rather than just random thoughts (Brown, Collins, & Duguid, 1989; Greeno, 1998; Lave & Wenger, 1991).

In summary, a theoretical framework composed of developmental and social learning theories suggests that learning by teaching is an effective pedagogical approach because: 1) social interaction and conflict between learners of all abilities benefits both the teacher and learner, 2) cognitive, behavioral, and environmental influences on social interactions impact why some teaching experiences can lead to learning, and 3) learning is more effective when performed in a situated environment. Learning-by-teaching supplies the learner with an opportunity to experience social interactions with peers and teachers, while modeling what they know about the content in an appropriate learning environment.

IMPLICATIONS FOR ENGINEERING EDUCATION

The descriptions and complementary research of the various learning-by-teaching approaches have shown that these pedagogical methods have the potential to enhance student learning if properly structured and executed. In engineering, specifically, the use of learning-by-teaching has grown, but the study of these interventions has been limited. The prominent studies and subsequent results have relied on student self-reported data. The earliest work by Goodlad et al. (1979), and later Saunders (1992), analyzed the specific affects of tutoring within engineering on the development of communication skills. Student self-reported data lends itself to the notion that a tutoring experience helps engineering students to improve their communication skills along with their ideas of their professional responsibilities. Magin & Churches (1995), and later Ramaswamy et al. (2001), extend Goodlad et al. and Saunders' work to include an analysis on developing not only communication skills, but also a deeper understanding of the content. Students expressed an increase in content gains attributed to the reformulation and reorganization of knowledge brought on by tutoring.

Cejka, Pickering, Conroy, Moretti, and Portsmore (2005), and later Carberry, Portsmore, and Rogers (2007), conducted two separate experiments on a group of undergraduate engineering students participating in K-12 engineering outreach. In Cejka et al.'s study, students were interviewed to determine the effects of K-12 outreach on their communication skills and sense of citizenship. Students self-reported both improvement in their communication skills and an enhanced sense of the civic responsibilities embedded in being an engineer. Carberry et al.'s study extended this study to include a quantitative analysis of student gains in engineering understanding as well as changes in student attitudes and confidence toward engineering design. Most students displayed increased understanding of the engineering design process accompanied by positive changes in attitudes and confidence toward engineering.

Cooperative learning in engineering has also been investigated in two studies by Johnson et al. (1991) and Smith (1996). These studies report that students felt they learned the material better, while teaching each other in a team context. The cooperative learning approach accomplished the goal of building team working skills, communication skills, positive interdependence, and accountability. In addition, Felder and Brent's (1994) analysis of cooperative learning in engineering notes that student professional skills are not the only aspect impacted by cooperative learning. Students involved in cooperative learning report deeper learning and increased positive attitudes toward engineering and themselves as a result of their cooperative learning experiences. The positive results found in these studies are tied to both the cooperative learning approach and the social benefits of learning STEM (science, technology, engineering, and mathematics) in small groups (Springer, Stanne, and Donovan, 1999; Smith, 2010).

The research results of these studies help advertise the use of learning-by-teaching approaches in engineering and start to analyze it's true potential. Future research is needed to build off of this base with an eye on conducting rigorous studies addressing engineering educator concerns about learning-by-teaching. The more feedback we can gather about current engineering teachers' use of learning-by-teaching, the better we can guide expanded use beyond teaching assistantships.

What does this mean for the future of engineering education? Engineering education is in a time of rigorous reflection upon the current methods used to educate the engineers of the future. According to reports like *Rising Above the Gathering Storm* (2005), K-12 education and higher education are two key areas where the United States needs to make changes if it wishes to uphold world leadership in engineering. Making changes starts with reforming classroom practice (Brown et al., 1989; Chickering & Gamson, 1987; Dewey, 1938; Fink, 2002; Lave & Wenger, 1991) and implementing appropriate pedagogical approaches. For K-college engineering educators, this means improving our ability to effectively teach students about specialized bodies of knowledge, application knowledge, and professional skills (Smith, 1988).

Learning-by-teaching approaches present an attractive pedagogical alternative for engineering classrooms. Examples of effective implementation include integrated service-learning projects like Purdue University's Engineering Projects in Community Service (EPICS) (Coyle, Jamieson, & Oakes, 2005), K-12 teaching opportunities including the former NSF GK-12 Program (deGrazia, Sullivan, Carlson, & Carlson, 2000) and Tufts University's Student Teacher Outreach Program (STOMP) (Portsmore, Rogers, & Pickering, 2003), and courses designed using cooperative learning (Mourtos, 2004; Smith, 1993, 1995). These teaching experiences for students provide them with an opportunity to evaluate how well they understand the material, while assisting their classmates and/or the community in understanding the material as well.

Implementation of these various learning-by-teaching approaches requires commitment to education and classroom change. Teachers need to develop a comfort level with student-driven classrooms where the teacher plays the role of guide, coach, and/or mentor. Using new and unfamiliar pedagogies that deviate from the traditional teacher-centered approaches will be successful only if the teacher is willing to devote initial buy-in time to learn how to teach using these alternative approaches. The major inhibitor of learning-by-teaching is the initial investment in time needed to begin using these techniques. We believe that this initial time spent is worth the investment if your administration supports your efforts. Designing activities that utilize teaching opportunities can start out as simple as translating what you as the teacher would have taught into an activity that the students teach. Comfort with this approach can easily lead to far more complex teaching opportunities for students. Like all other forms of pedagogy, this approach takes time to learn. Teaching, on the part of the teacher and the student, should not be viewed as something you can automatically do when you walk into a classroom nor should it be something that is rigid and fixed. Time should be spent learning how to effectively help students learn. With support from your administration, learning-by-teaching can be an effective and easily implemented pedagogy to enhance student learning.

CONCLUSION

Learning-by-teaching has been reviewed and presented as an alternative to traditional teacher-centered approaches and to help faculty considering a learning-by-teaching approach anticipate how the approach might lead to improved learning. Classroom circumstances, including reduced contact hours with increased amounts of content taught, have driven educators to default to lecture. Lecture may increase efficiency of material presented, but often limits what students actually learn. Using learning-by-teaching approaches provides students with an opportunity to learn how to learn and places the responsibility of learning in the hands of the students. Learning-by-teaching should be carefully implemented and studied at all levels to determine how strong an increase in conceptual understanding can be achieved in various contexts, thus determining how best to utilize learning-by-teaching as one approach to improving engineering education on a grand scale.

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AUTHORS

Adam R. Carberry, Ph.D., is an Assistant Professor at Arizona State University in the College of Technology & Innovation's Department of Engineering. He earned a B.S. in Materials Science Engineering from Alfred University, and received his M.S. and Ph.D., both from Tufts University, in Chemistry and Engineering Education respectively. Dr. Carberry was previously an employee of the Tufts' Center for Engineering Education and Outreach and manager of the Student Teacher Outreach Mentorship Program (STOMP).

Matthew W. Ohland, Ph.D., is Associate Professor of Engineering Education at Purdue University. He holds a Ph.D. in Civil Engineering with a minor in Education from the University of Florida and degrees in Mechanical Engineering and Materials Engineering from Rensselaer Polytechnic Institute and in Engineering and Religion from Swarthmore College. He was previously Associate Professor of General Engineering at Clemson University. As a National Science Foundation Postdoctoral Fellow, he was the Assistant Director of the Southeastern University and College Coalition for Engineering Education. He is past President of Tau Beta Pi, past Chair of the Educational Research and Methods Division of ASEE, and is on the Administrative Committee of the IEEE Education Society. He has been recognized with best paper awards in multiple conferences and a journal, and has received teaching awards from both Clemson and Purdue.