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The Problem Solving Studio: An Apprenticeship Environment for Aspiring Engineers

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ABSTRACT

This paper describes the problem-solving studio (PSS) learning environment. PSS was designed to teach students how to solve difficult analytical engineering problems without resorting to rote memorization of algorithms, while at the same time developing their deep conceptual understanding of the course topics. There are several key features of PSS. First, students work in teams of two to solve problems, working at the same table with another team of two. The student teams and tables are stable, remaining together for most of the semester. The teams work in a public, shared problem-solving space that allows in-class mentors (near peers of the students) and the instructor to observe and critique their work. The public nature of the work enables the instructor to provide students with real-time, situated feedback. In addition, it enables the instructor to tailor the challenge level to the needs of each team, such that the problem is too difficult for any one student to solve on their own, but reasonable enough that the team can solve it together, given the support that the PSS environment provides. We call this targeted adjustment of the problem's difficulty *dynamic scaffolding*. PSS provides the support students need through a specific set of participant structures that govern how the instructors, in-class mentors, and students interact during class. This paper describes the PSS approach and how it has been implemented in an entry-level course at Georgia Tech called "Conservation Principles of Biomedical Engineering (BMED 2210)". Our results show that even though PSS emphasizes engineering problem-solving skills, the students' conceptual understanding of the material significantly improves, as measured by Shallcross' material and energy balances concept inventory. The implications of our work, particularly with respect to the use of PSS in flipped classrooms, are discussed.

Key words: studio, problem-solving, problem-solving studio, flipped classroom, dynamic scaffolding, collaborative learning, apprenticeship, engineering, material and energy balances, near peers

INTRODUCTION

A key objective of many first-year engineering courses is to introduce undergraduates to the approaches engineers take to solve problems. In an effort to apprentice students to the engineering problem solving approach, many entry-level engineering textbooks provide students with a step-by-step procedure that is remarkably similar across multiple domains of engineering (Craig 1996; Himmelblau and Riggs 2004; McGill and King 1995). These procedures encourage the problem solver to 1) read and understand the problem, 2) abstract the key features of the problem to create an idealized model of the system, often in the form of a diagram, 3) use the diagram, in concert with fundamental principles, to generate and solve a mathematical model, and 4) check whether or not the answer is reasonable. These steps are explicitly listed and explained in the textbooks and course instructors emphasize and teach these steps to their students. Nevertheless, large numbers of students continue to struggle in, and sometimes fail to pass, entry level engineering courses (Felder et al. 1994; Suresh 2006).

One reason for this is that many novice engineering students are ill-equipped to solve engineering problems. Many students enter their first engineering course adept at solving relatively simple, well-structured problems but with little prior experience in dealing with ill-structured, complex problems (Hestenes, Wells, and Swackhamer 1992; Rosengrant, Van Heuvelen, and Etkina 2009; Jonassen and Hung 2008). As a result, most students come to their first engineering course with a well-practiced strategy that uses a rote problem solving approach in which they 1) write down the known and unknown variables they find in the problem statement, 2) search for a formula or equation that uses these variables, and then 3) enter the numbers into the formula and calculate an answer (Rosengrant, Van Heuvelen, and Etkina 2009). Indeed, a common lament of engineering professors is that their students persist in using ineffective “plug-and-chug” approaches in which they search for problems with similar surface features to the one they are trying to solve and then plug their numbers into the equations that worked for these similar problems, hoping this will lead to the correct answer. Little or no attention is paid to step two of the textbook problem-solving method which recommends creating an idealized diagrammatic model of the system described in the problem statement and using the diagram to generate the relevant mathematical equations (Bella 2003; Waller and Le Doux 2014; Waller, Newstetter, and Le Doux 2013; Waller, Le Doux, and Newstetter 2013).

Similar observations have been made in chemistry courses. Several studies have shown that the majority of students in high school and college chemistry courses rely almost exclusively on an algorithmic approach to quantitative problem solving and that experience with an algorithmic approach does not facilitate conceptual understanding (Anamuah Mensah 1986; Bunce, Gabel, and Samuel 1991; Gabel, Sherwood, and Enochs 1984; Herron and Greenbowe 1986; Lythcott 1990; Niaz and Robinson 1992). Cracolice et al., in a study of students’ algorithmic and conceptual problem-solving abilities in a first-semester general chemistry course, concluded that students have no choice other than to be algorithmic problem solvers because their reasoning skills are not sufficiently developed to allow them to successfully solve conceptual problems (Cracolice, Deming, and Ehlert 2008). The authors noted that despite an increased emphasis in the past several years on conceptual understanding and connecting concepts to problem-solving in textbooks and curricula, the algorithmic–conceptual gap has remained relatively constant. Bodner, as far back as 1992, suggested that solving the algorithmic-conceptual gap can not be achieved through curriculum changes alone; rather, changes must be made in how the curriculum is delivered (Bodner 1992). That is, if we want students to learn how to become more effective problem solvers, who do not rely on rote memorization of procedures, formulas, and algorithms to solve problems, than we need to design and implement more effective learning environments.

OVERVIEW OF THE PROBLEM-SOLVING STUDIO

Development of the problem-solving studio

To address this need, a powerful learning environment we call the *problem-solving studio (PSS)* was developed by one of us (J.L.) for teaching engineering ways of thinking and analytical problem solving skills. The PSS approach refers to a specific set of *participant structures* that govern how the instructors, in-class mentors, and students interact during class, with each other and with the objects of learning (Philips 1972). PSS is silent with respect to what activities, if any, the instructor should require their students to engage in outside of class. PSS was first implemented in 2008 in a large biomedical engineering department as an experimental approach for teaching a required entry-level course called “Conservation Principles of Biomedical Engineering” (aka BMED 2210), then further developed over several years via an informal design research process in which changes to the learning environment were made based on the professor’s observations, feedback from his students, and in consultation with a learning scientist who was a full-time faculty member in his department. More recently, we have begun to carry out formal research studies of the learning environment to deepen our understanding of its key features and how they affect students’ motivation and learning.

As the PSS approach was being developed, advances in technology and multimedia infrastructure stimulated significant interest in the last two to three years in using the “flipped classroom” to teach engineering courses (Jahnke and Norberg 2013; Ng 2015a). The term flipped classroom, in its broadest sense, refers to a learning environment in which the professor puts their lectures online, thereby freeing up classroom time for other learning activities which are intended to be more interactive and engaging (Ng 2015b; Larcara 2014; Gardner 2015). The term flipped classroom says nothing, however, about the nature of these in-class activities or how they are structured, other than to suggest that they are not full lectures. The PSS learning environment potentially fills this void because although PSS does not require instructors to put their lectures online, it is a useful model of how they can structure the in-class time they have freed up by putting their lectures online. So, in summary, the term flipped classroom specifically refers to the out of class activity of requiring students to view online lectures, whereas we use the term *problem-solving studio* (PSS) to refer to how we structure the time we have with our students in the classroom.

The problem-solving studio and the architecture design studio: a comparison

The name “Problem-Solving Studio” was chosen because the PSS approach shares several significant features with the architectural design studio. It is useful, therefore, to briefly reflect on the similarities and differences between the two approaches. The architecture design studio tradition was first established at the Ecole des Beaus-Arts in Paris, an influential educational institution that was founded in 1648 (Ockman and Williamson 2012). Currently, architecture students often begin their studies of design in their first year, in studios that are led by a studiomaster, who is assisted by studio teachers, or critics, who oversee the students’ work in a particular section of the large room (i.e., studio) where all the students of the same level work side-by-side (Dinham 1987). Students’ work centers on design problems, which takes precedence over lectures as the primary teaching tool (Ockman and Williamson 2012). Student work on a project begins when they are handed a one to five page project description, after which they spend their time studying the requirements, planning general approaches, and making sketches of their solutions that they iteratively develop (Dinham 1987). Their work culminates in their solution to the design problem, which often includes a number of drawings and a physical model.

The primary means by which architecture students receive feedback during the course of a project is through the desk crit. The desk crit is a brief event that occurs repeatedly on any given day in the studio. The critic moves through the studio room and meets with students, one-on-one, either randomly or through informal appointments, to discuss their work (Dinham 1987). The critic also meets with groups of students to discuss points that are relevant to all students. Occasionally, perhaps one to three times during the course of a project, all the students will pin up their work on a wall and the critic will move from one student’s work to the next, critiquing their work publicly in front of all the students (Dinham 1987). Students present their final projects to a jury of faculty and local practitioners who also critique their work in front of the other students, who are expected to learn from these reviews (Ockman and Williamson 2012; Dinham 1987).

PSS shares several significant features with the architecture studio. As with architecture students, engineering students first experience the PSS environment early in their undergraduate careers. Their primary activity in PSS is solving engineering problems, work which takes precedence over the lecture as the main method for teaching. The importance of creating sketches and engineering diagrams and using them as thinking tools is heavily emphasized. In addition, the students' work is carried out in a public space (that is, it is visible to other students and the instructor) and the instructor frequently enters into a discussion with them about their work. These discussions are what Ruiz-Primo calls "informal formative assessments" in which the instructor seeks to make a student's "thinking explicit in an unobtrusive manner so that it can be examined, questioned, and shaped as an active object of constructive learning" (Ruiz-Primo 2011). The instructor does this by asking open-ended questions to get the students talking about their problem solving processes, such as "How is it going?" or "What assumptions did you make and why?" or "Can you summarize for me what you have done so far?" In addition, older students, who performed well in the course in a prior semester, serve as in-class mentors and roam the room to assist the instructor in providing feedback to the students. Similarly, at the Ecole des Beaus-Arts, it was common practice for the older students (the anciens) to help the newer students (the nouveaux) (Ockman and Williamson 2012). The in-class mentors are not formally trained for their role, but the instructor mentors them during PSS and during as-needed meetings outside of class. Finally, both use the apprenticeship model of learning, in which the novice learns by observing the expert undertake a specific task, and then attempts the same task while getting feedback and guidance from the expert (Collins, Brown, and Newman, 1989). In PSS, the students are engaged in a cognitive apprenticeship with their instructor because the tasks that are being learned are intellectual, not physical, in nature (Newstetter 2005). Key to this kind of instructional relationship is the support the expert provides in the form of observations, evaluations, and just-in-time help (Newstetter 2005). The expert gradually reduces the amount of support they provide over time as the novice begins to master the task, ultimately leading to the novice working alone (Newstetter 2005).

Although PSS and the architecture design studio approaches have a number of similarities, there are some significant differences. First, in PSS, students work on solving analytical engineering problems, not design problems. Second, the students work in teams of two at a table with another team of two students to collaboratively solve the problem. Third, students' work is process-oriented, not product-oriented. The fundamental goal of the teamwork is to learn good problem solving processes, not to produce a specific design, product, or report. When students' knowledge is assessed via quizzes and tests, their work is graded based on the process they used to solve the problems, with little weight given to whether or not they ultimately came up with the correct final answer.

The problem-solving studio and other active learning environments: a comparison

Later in this paper, we elaborate on the details of the problem-solving studio but it is useful to compare its general characteristics to other active and cooperative learning environments (see Table 1). Several features distinguish it from formal cooperative learning, Process Oriented Guided

	PSS	Informal Cooperative Learning	Formal Cooperative Learning	POGIL	Scale-up	Laboratory Courses
Environment	classroom with tables; pairs of students on each long side	lecture style room	various classrooms; perhaps tables	various classrooms; perhaps tables	classroom with tables for 9 people and 3 computers	laboratory
Length of engagement	1.5 - 2 hours per class; 25 classes per semester	2-10 minutes in class between mini-lectures	several class days to full semester	50 minute class period	50-120 minutes per class	2-3 hours per lab; 5-12 labs per semester
Activities	students solve complex problems that engage multiple concepts	students develop short answers to questions, brainstorm, solve small problems	students work together on large projects	students work to complete worksheets that guide them through the process of learning	hands-on activities, simulations, or interesting questions and problems	students follow instructions to reproduce experiments with known results
Size of groups	2 students per team; 2 teams per table	usually pairs	small groups of 2 – 6 students	2-6 students	3 teams of 3 at each table	2-3 students
Role assignment	students negotiate together	if roles are used, randomly assigned	students are assigned roles that rotate	students are assigned roles that rotate	not specified	student negotiate together
Problem-solving space	blotter pads shared by 2 students	individual notebooks	individual or shared notebooks	each student has copy of worksheet; one team solution submitted	each team shares a computer	lab bench with equipment; individual lab notebooks

Table 1. A comparison of PSS to other similar learning environments.

Inquiry Learning (POGIL), Scale-up, and lab courses (Crouch & Mazur, 2001; Heller, Keith, & Anderson, 1997; D. W. Johnson, Johnson, & Smith, 1998b; 1998a; Moog, Creegan, Hanson, Spencer, & Straumanis, 2006; Richards, Kustusch, Ding, & Beichner, 2008; Smith, 2000). The students are partnered all semester rather than for a single class or project. Although they are given complex problems to solve, they are not doing guided inquiry via worksheets or lab procedures. Students in PSS share the writing task, but roles are negotiated between the students rather than being assigned. In both PSS and Scale-up, the instructor circulates to assist the students, but PSS also includes interactions with near-peer mentors. In Scale-up, student teams share a computer, while in PSS students work together on a shared large pad of paper. This creates a public, shared problem-solving space that, to our knowledge, is unique to PSS. In summary, although PSS incorporates some features of different instantiations of cooperative learning, its integrated components set it apart.

Description of the entry-level biomedical engineering course used to develop the PSS approach.

Next, we describe the course we used to develop the PSS learning environment, including its list of topics. BMED 2210, “Conservation Principles of Biomedical Engineering”, is usually among the first required engineering courses that a biomedical engineering student takes at Georgia Tech. It is a 4-credit hour course. To register for the course, students must have earned a C or better in both Physics I and General Chemistry I. Physics I exposes students to Newton's laws and the principles of momentum and energy conservation. General Chemistry I covers the fundamental laws and theories of chemical reactions. In combination, these pre-requisite courses provide students with a solid grounding in the fundamental principles of physics and chemistry needed to succeed in the course. Most students take this course in their 2nd year in college. Although the focus of this paper is BMED 2210, we believe that PSS is appropriate for use in any level problem-solving course.

The purpose of BMED 2210, as stated in the syllabus, is to prepare students to "analyze and solve problems involving complex biological systems by applying principles of mass and energy conservation. More fundamentally, this course introduces students to the engineering approach to problem solving. This includes breaking a system down into its components, establishing the relationships between known and unknown system variables, assembling the information needed to solve for the unknowns, then obtaining the solution." By the end of the course, students are expected to know the basics of conducting engineering calculations and be able to apply these concepts and principles to the analysis of physiological systems. The primary textbook for the course is "Bioengineering Fundamentals" by Saterbak, McIntire, and San (SMS) (Saterbak, San, and McIntire 2007). Students are also encouraged to consult Himmelblau and Rigg's (H&R) "Basic Principles and Calculations in Chemical Engineering, 8th edition" as a supplemental text (Himmelblau and Riggs 2004). The topical outline of the course is provided below (Table 2).

Week	Topic
1	Introductory concepts: units, significant figures, properties, estimation, diagrams
2	Material balances for single-unit, non-reacting systems
3	Material balances for multi-unit, non-reacting systems
4	Material balances for single-unit, reacting systems
5	Material balances for multi-unit, reacting systems
6	Material balances for systems with gases: ideal gas law
7	Material balances for systems with multiple phases: phase diagrams and vapor pressure
8	Material balances for systems with multiple phases: saturation and partial saturation
9	Introduction to energy balances: terminology, types of energy that must be accounted for
10	Calculating changes in energy at the molecular level: internal energy and enthalpy
11	Energy balances for non-reacting systems
12/13	Energy balances for reacting systems
14	Material and energy balances for non-steady-state systems
15	Review

Table 2. Topical outline of BMED 2210.

DETAILED STRUCTURE OF THE PROBLEM-SOLVING STUDIO

To support the learning of these concepts and skills, we immerse our students in the PSS learning environment, which is distinctive in a number of significant ways. First, although the contact time is the same for PSS as for the lecture-based version of the course (4 hours), the PSS class meets less often for longer periods of time: 2 times for 2 hours each in PSS versus 4 times for 1 hour each in the lecture-based course.

Physical Layout of the Course

In addition, unlike a traditional course where the professor uses most of their contact time with the students to lecture, PSS employs a number of different kinds of interactions. To understand how these interactions take place, it is important to understand the physical setting of the room, and how the participants and learning materials are organized. The first major difference one observes is the physical setup of the room. In the Biomedical Engineering Department at Georgia Tech we have outfitted two classrooms to support PSS. Each classroom can hold up to 48 students seated at 12 tables. All the tables and chairs are on wheels. Ideally, the furniture is configured so that each table is isolated so that there is sufficient space between the tables to make it easy for the instructor to move about the classroom and to quickly reach any student or table. There are several whiteboards distributed among the walls of the room that are magnetized so that the students' work can be posted for review and discussion. This setup allows the instructor and students to configure the room in ways they believe best supports their learning for that particular day's activities. It is important to note that this specific setup is not required to implement PSS. PSS can be used in any kind of classroom as long as students can work in teams of two and the instructor and in-class mentors are able to observe the team's work and carry out a desk crit. Nevertheless, it is preferable to implement PSS in a classroom that can be reconfigured as needed to optimally support the planned learning activities.

Students solve problems that are more complex and less structured than typical textbook problems

Having described the physical configuration of a typical PSS classroom, we will now describe what the classroom looks like when students are working together to solve an engineering problem. The primary purpose of BMED 2210 is to develop the students' analytical problem solving skills. It is not a design course. Nevertheless, for the most part, we give students problems that are challenging enough that the students solve only one to three problems in a typical 2-hour PSS class session. We find it helpful to use Jonassen and Hung's problem difficulty classification scheme to describe the kinds of problems we ask PSS students to solve (Jonassen and Hung 2008). Jonassen and Hung propose that a problem's difficulty is a function of its complexity and its structuredness. The complexity of a problem manifests itself in "the breadth of knowledge required, the difficulty level of comprehending and applying the concepts involved, the skill and knowledge levels required to solve the problem, and the degree of nonlinearity of the relations among the variables within the problem space". The factors that characterize the structuredness of a problem include "known versus unknown states of the problem, regular versus unconventional uses of rules and principles involved, stated constraints versus hidden constraints, predictable operators versus unprescribed operators, a preferred and prescribed solution versus multiple viable solutions, and definite versus vague criteria for evaluating the solutions" (Jonassen 1997).

Using Jonassen and Hung's terminology, the problems we ask our students to solve in PSS are reasonably well-structured but somewhat complex. We frequently base the problems we give our students on problems from their textbooks, but we often modify them to make them more ill-structured and complex. Generally, we make the problems we assign more ill-structured by reducing their transparency by increasing the number of unknowns and by assigning or altering problem statements to increase the number of possible ways to solve the problem (that is, we increase the number of "legitimate competing alternatives") (Jonassen and Hung 2008). In addition, we steadily increase the complexity of the problems throughout the semester, particularly with respect to the intricacy of the solution process. That is, as the semester progresses, we tend to use problems with longer path lengths from the initial state to the goal state of the problem and we increase the number of relations and concepts the students need to process while solving the problems. The reduced structure and increased complexity of these problems provides students with multiple options for how to approach and solve them, which leads to robust discussions among the students and instructors. Please see Table 4 in the appendix for a detailed illustration of this approach.

Dynamic scaffolding is used to provide students with the appropriate level of challenge

According to Jonassen, because the PSS problem is less well-structured and more complex than the textbook problem, it will be more difficult to solve (Jonassen and Hung 2008). The instructional challenge is to present each team, each table, and the entire class with a problem that is appropriately challenging, but not so difficult that students make little to no progress for an extended period of time. Vygotsky conceptualized the difference between what an individual can do on their own versus what they can do with the help of a more knowledgeable other, such as a peer, instructor, or through some other kind of instructional support (aka scaffolding), as the zone of proximal development (ZPD) (Vygotksy 1978). The role of the instructor, then, is to provide support and assistance to enable the student to operate at a higher level than they could if they were working on their own. The support that the instructor or the learning environment provides is called scaffolding

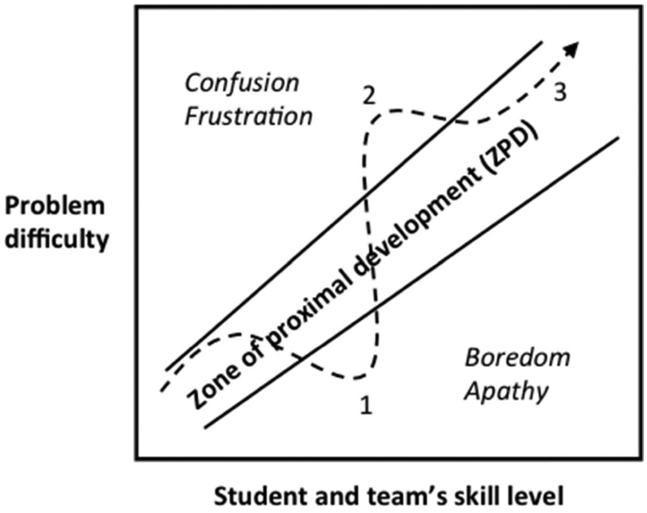

Figure 1. The relationship between problem difficulty, student's skill level, and the zone of proximal development (ZPD).

(Wood, Bruner, and Ross 1976). Ideally, students are operating within their ZPD; otherwise, they will become confused and discouraged if the work they are doing is too far beyond their capabilities, or bored and disinterested if the work they are doing is too beneath their current capabilities (Figure 1).

Typically, students within a class are at many different levels of development for any given skill, concept, or problem. In an ideal learning environment, each student would be operating within his or her own ZPD. This is difficult to achieve in a traditional lecture-based course because the instructor can deliver only one lecture at a time, which may be at a level that is appropriate for only some of the students (Exley and Dennick 2004). If there are differences in students' comprehension, the lecturer is not likely to detect or respond to this since the students' thinking is not made visible in a traditional lecture setting. In contrast, several features of PSS make it possible to dynamically modify in real-time the scaffolding that is provided to the students, either at the local level of an individual student-team or table, or at the global level of the entire class, in order to keep as many students as possible within their zone of proximal development (ZPD). We call this dynamic scaffolding.

An instructor can dynamically scaffold students' learning by ratcheting up or down the difficulty of a problem, by making it less or more complex or by making it less or more structured, as described above. Typically, in PSS, the instructor would begin by presenting the entire class with a problem that they believe is sufficiently difficult to be within the ZPD of the class' more advanced students. The instructor would then need to assess, in real-time, the progress that students are making on the problem to determine if, and for whom, the problem's difficulty needs to be modified. The instructor could choose to reduce or increase the difficulty of a problem for a single team or table, or for the entire class.

The problem-solving studio uses multiple participant structures to support student learning

PSS enables instructors to monitor students' progress in real-time through the participant structures it creates. Susan Philips defined "participant structures" as the "ways of arranging verbal interaction with students, for communicating different types of educational material, and for providing variation in the presentation of the same material" (Philips 1972). Philips found that student learning can be profoundly impacted by the participant structures that are used, both because they strongly influence how students interact and communicate with each other and with the instructor, and because some learning objectives are best achieved through "one sort of participant structuring rather than another" (Philips 1972).

The primary participant structure of PSS is the team of two students who problem-solve together on a publicly visible problem-solving space (we typically use 17"x22" pads of blotter paper). The instructor challenges the students with a problem, either by describing the problem statement orally, writing it on a whiteboard, or by handing them a printed problem statement. The student pairs then begin working on the problem together. In most cases, one student writes on the blotter pad while explaining what they are doing to their partner. The partner who is not writing actively engages in the problem-solving process by listening carefully, agreeing with or critiquing what their partner is doing, and suggesting their own ideas about how to proceed. Every few minutes the students switch who is holding the pen. The students negotiate who holds the pen and for how long.

There are three key features of this participant structure that we believe promote learning (see Figure 2). First and foremost, it requires students to explain and defend the approaches they take to solve the problem. Self-explanation such as this promotes learning and facilitates problem solving by helping the problem solver draw conclusions and make inferences from the problem statement when critical information is missing (Wickelgren 1974; Chi et al. 1989). Second, the two students must work together to solve the problem. This requires students to argue their points, to communicate clearly and persuasively, and to negotiate with a peer which route to take when solving the problem (John-Steiner and Mahn 1996; Doolittle 1995). Finally, the third key feature of this participant structure is that the team's work is publicly visible, to the other team at their table, as well as to the in-class mentors and the instructor.

The second participant structure of PSS is when the pair of teams that are seated together at a table confer with each other to solve the problem. The teams form a kind of distributed cognitive network in which they leverage each other's skill sets and knowledge bases to improve their

Figure 2. The key participant structures of PSS. Panel A shows students working on blotter pads in teams of 2, across from another team of 2 at the same table. Panel B shows an in-class mentor, a "near-peer", working with a student team. Panel C shows the instructor mentoring a table of 4 students.

ability to interpret the problem and navigate their way towards a solution (Hutchins 2006). The student teams confer with each other when they find themselves struggling with a problem, which effectively expands their capabilities, stretching their collective zone of proximal development a bit further. Importantly, the students work together in the same teams and at the same table for most of the course. Students choose their own teams initially, but two to three weeks into the course the instructor assigns permanent teams. The teams are heterogeneous in terms of the students' scores on the weekly quizzes and the early concept inventory (which we discuss in more detail later), although each student is given the opportunity to anonymously identify one student they want to be at their table. We have found that giving students a say in who will be at their table reduce their resistance to this change, and in fact many students welcome the change. Stable teams of this size, sometimes called cooperative base groups, enables students to develop a sense of trust in, and responsibility to, each other, which improves the quality and quantity of learning (D. W. Johnson & Johnson, 1999).

The third participant structure of PSS is when an in-class mentor (a near peer) or the instructor interacts with a team or table of students, initiated by the students or by the mentor/instructor (Liberatore, 2013; Prather, Rudolph, & Brissenden, 2011). The students raise their hands when they want to interact with an in-class mentor or the instructor. Most often, students request this interaction when they have a question about the problem statement, want to see if they are on the right track, are not sure how to proceed, or want feedback on their solution. Sometimes the instructor or in-class mentors initiate this structure without waiting for the students to request it. The instructor forms this structure to thoroughly assess how the students are doing, to determine if their approach is sound or not, and to see if they have any significant misconceptions. While in this structure, the in-class mentors and instructors do not directly tell the students what to do or how to proceed, nor do they perform any calculations or problem solving for the students. Rather, they primarily interact with the students by asking questions, to model for them the kinds of probing questions experts ask themselves as they progress through a problem. Even if the students have completed the problem and have the correct numerical answer, the in-class mentors and instructor thoroughly review, with the students, the approach the students took to solve the problem to ensure they understood the principles that were in play and to ensure that the problem-solving approaches they took were sound, before they release the students to begin working on the next problem in the problem set.

The discourse that takes place within this participant structure may differ, depending on whether the instructor is an in-class mentor or the professor (Chi & Wylie, 2014). This is because the professor has more experience and expertise in the topics of the course than the in-class mentors. This can be advantageous, because the instructor may be better prepared to troubleshoot student solutions, and better able to guide students in discussions about the deep principles that underlie the problem. The professor's expertise can also be a disadvantage under some circumstances, because much of their knowledge will be tacit, which is knowledge that is unconscious and can not be written or verbalized. In contrast, less of the in-class mentors' knowledge, having recently taken the course, will be tacit (Polyani 1966; M. Chi, Glaser, and Rees 1982). They are skilled participants, not experts. These skilled participants serve as "near peer" role models, which in some circumstances may be better suited than the expert to coach the students with questions because they may find it easier to verbalize their ways of thinking to the students. According to Murphey, near peers are "more psychologically attractive" to students because their "excellence seems more possible and easy to see and replicate because they are in some ways already very similar to" them (Murphey 1996).

This process, in which the instructor and student reflect on the challenges the student encounters while solving a problem, and take action based on that reflection to enhance learning during the learning process, is called *formative assessment* (Cowie & Bell, 2010). PSS makes possible the dynamic formative assessment of the student teams by the fact that the teams are working together in a shared problem-solving space on the desk blotter pads. This ability to dynamically assess student work in real-time is critical to the success of PSS, because as it is taking place, both the students and the instructor are receiving situated feedback. The students are getting feedback on their problem-solving approach and the instructor is getting feedback on how well the students are performing and how they are experiencing the problem. In parallel, the instructor, after observing a small number of teams, can gauge whether or not specific teams, or perhaps the entire class, need additional support to progress through the problem. This situated feedback enables the instructor to decide, in real-time, whether or not to ratchet up or down the problem difficulty, for one team or table, or for the entire class. In addition, PSS instructors learn very rapidly what the conceptual difficulties are that students struggle with most, and what kinds of problems and lines of questioning best help them overcome these challenges. We believe that PSS instructors, because they see so much of their students work, will make rapid advances in their pedagogical content knowledge. Pedagogical content knowledge is a key component of teaching expertise and, according to Shulman "includes an understanding of what makes the learning of specific concepts easy or difficult: the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning" (Shulman 1986).

The fourth participant structure is when the instructor interacts with all the students at the same time. Typically this is used only 3 or 4 times during a 2-hour class period for 3 to 5 minutes at a time. It is usually implemented when the instructor sees that multiple groups are struggling with similar issues. The instructor most often uses this structure to carry out a "just-in-time discussion", which the students are highly motivated to participate in because they are engaged with, and challenged by, the problem and are hungry for insights that will help them figure out how to get past the intellectual obstacles that are blocking their progress (Schwartz and Bransford 1998). Often, the instructor uses these discussions to draw students' attention to the key concepts or skills needed to solve the current problem or to model problem solving strategies and heuristics. In addition, the instructor can use this time to develop students' metacognitive skills by teaching them the importance of reflecting on their performance, helping them identify which concepts and problem-solving approaches that they still need to work on, and encouraging them to create an action plan to overcome these intellectual shortcomings.

We are often asked how we encourage students to engage in the problem-solving studio environment and if some students resist. Our experience has been that the vast majority of students participate right away, enthusiastically. There is an initial "training period" during the first week or two, during which we remind the students at the beginning of class to use their blotter pads, to work in teams of two at tables of four, and to share the pen. But after the first few meetings, the students begin doing this automatically, without being reminded. We believe that the students are engaged because they feel safe and supported: they are not being graded, they work with a partner at a table with three other students, and they get real-time assistance from the in-class mentors and the instructor whenever they ask for it. In addition, their work is public, which motivates the students to remain engaged since the in-class mentors and the instructor can, and often do, join their group to carry out an impromptu desk crit. We find that for a class of 48 students, two in-class mentors and one instructor are needed to provide sufficient real-time support for the students.

Multiple types of formative assessment are used to assess student learning

An important feature of PSS is that it clearly demarcates formative assessments from summative assessments (i.e., graded activities) of student learning. In PSS, except when the instructor is addressing the entire class, formative assessment is happening nearly continuously for every student in the class. This is made possible because the students are working together, explaining their thinking processes to each other out loud and co-constructing solutions to the problem they are working on in a shared problem-solving space that is public. The instructor and in-class mentors roam about the room and listen to and see each team's approach by strolling near their table and eavesdropping or by looking at what they have written on their blotter pad. Instructors and in-class mentors often then initiate a dialogue with the team or table they are observing to challenge the team on the approach they are taking, to learn more about how they are thinking about the problem, or to ask them what difficulties or challenges they are encountering. These conversations are primarily propelled through questions that the instructor asks the students, questions that are open-ended but targeted with the intent to stimulate the students' metacognitive thinking and to probe specific aspects of their knowledge relevant to the problem they are solving. These conversations frequently reveal student misconceptions, even when a student team appears to be on the right track, and provide the instructor with the information needed to help the students recognize their misconceptions and to adjust the problem difficulty as needed (i.e. to dynamically scaffold). It is important that the students know they are not being graded or judged at this point. This establishes the studio time as a safe time for students to explore, to challenge themselves, to admit they don't understand, and to seek help by asking questions.

In addition to the real-time feedback students receive while solving problems with their teammates in PSS, we also give students the opportunity to experience a quiz-like setting in which they are given a defined period of time to solve a problem on their own first, before discussing it with their teammates. These practice quizzes are given immediately after students turn in that week's homework, and they are intended to provide students with feedback on how well they understand the homework material. Briefly, on practice quiz days, students turn in their homework and then immediately begin working on a practice quiz. Most of the time, the practice quiz is an old quiz that was given to a previous semester's class as a graded assignment. The students work on the practice quiz on their own, as if it were a real quiz, for about 20 minutes, after which they discuss the quiz with their tablemates for about 5 minutes. Finally, a class discussion is held about the practice quiz between the students and the instructor, until the students' questions about the quiz are answered. The practice quizzes give the students feedback about their readiness for the graded quiz, which is taken two days later during the next class period, and it models for the students what they should be doing on their own, which is to periodically test themselves, under a quiz or test-like setting, to evaluate how well they know the material before they are formally evaluated in class on a graded quiz or test. Several recent studies suggest that pre-testing students in this way may lead to significant gains in learning (Agarwal et al. 2008; Bjork and Storm 2011).

Out-of-class learning assignments and summative assessments of student learning

PSS is an approach for how to structure in-class learning activities that provides students with copious amounts of formative, real-time feedback, usually in a group setting. PSS does not require particular out-of-class activities nor does it determine how student learning should be assessed. As a result, there is a wide range of possible ways PSS instructors can further support student learning through out-of-class learning activities and through summative assessments for grades. However, these out-of-class activities and summative assessments should be congruent with the PSS approach. For example, grading exams on a curve to achieve a particular grade distribution would not be congruent with the collaborative learning in PSS and may undermine students' learning in pairs (Archer-Kath, 2010; Smith, 1996).

Here we describe the approaches we use when we teach BMED 2210 using the PSS approach. Each week the classroom activities focus on a new concept having to do with using mass and energy balances to solve problems. In addition to the in-class PSS problems and practice quizzes, students are expected to carry out the following learning activities to help them master the material: 1) weekly assigned readings from the required textbook or from other sources such as a supplemental textbook or course notes; 2) weekly homework assignments that reinforce and go into greater depth the concepts and problem-solving approaches that were focused on in PSS that week; 3) weekly quizzes that focus on the material that was covered in the previous week's homework assignment; 4) two mid-term exams; and a 5) cumulative final exam. In general, we do not quiz the students on the assigned reading. Instead, we expect students to be motivated to complete the assigned reading because they do not want to be left behind by their teammate, and because they know their work is publicly visible and will be evaluated multiple times per class by the instructor or the in-class mentor.

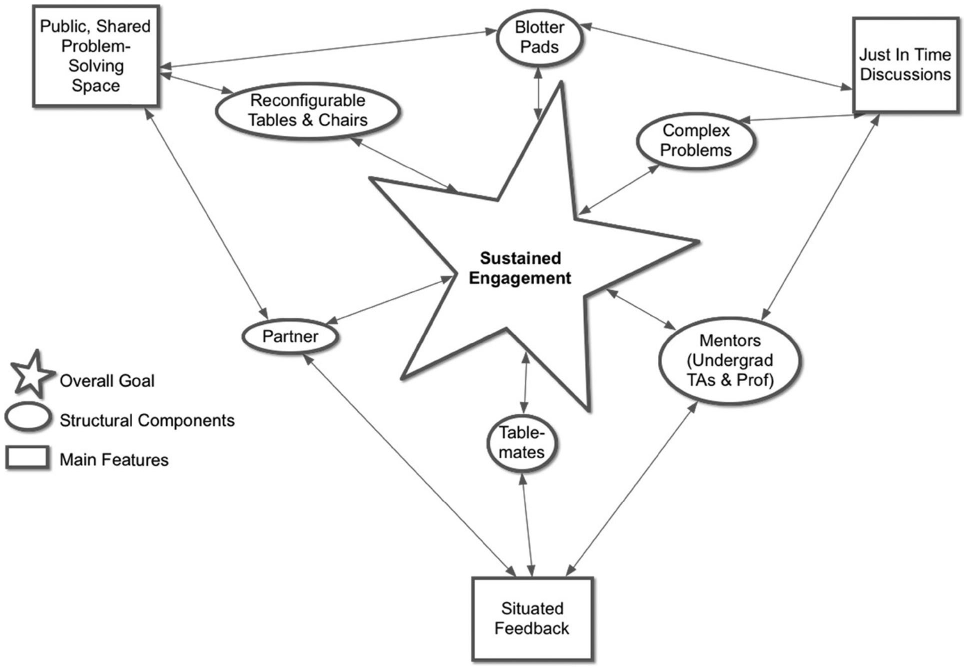

Figure 3. Key features of the PSS learning environment.

Figure 3 summarizes the essential elements of the Problem Solving Studio. The overall goal of PSS is to have the students in sustained engagement with the course content. This is achieved by the three main features: a public, shared problem-solving space, just in time discussions, and situated feedback. These features are supported by a variety of structural elements, including reconfigurable tables and chairs, blotter pads, complex problems, mentors, tablemates, and partners. The arrows denote the primary linkages among items. In addition, we have posted a three-minute video that depicts PSS: http://resourcecenters2015.videohall.com/posters/502.

METHODS AND RESULTS

Quantitative analysis of the impact of PSS on students' conceptual understanding

We developed PSS to address the need for new learning environments that teach students engineering problem-solving approaches that do not rely on the rote use of memorized algorithms and that facilitates deep conceptual understanding. Since the focus of PSS is on the problem solving process, concerns may arise regarding how well students learn the concepts of the course. To investigate this concern, we studied a convenience sample of students who enrolled in BMED 2210

Variable	Number (%)
Gender	
Males	64 (47%)
Females	71 (53%)
Ethnicity	
White / Caucasian	52 (39%)
East Asian	28 (21%)
South Asian	28 (21%)
Hispanic	13 (9.6%)
Black / African-American	5 (3.7%)

Table 3. Demographics of study participants.

during the following semesters: Fall 2012, Spring 2013, Fall 2013, and Spring 2014. Each course was taught by one of the authors (J.L.) using the PSS approach. The participants' demographics are summarized in Table 3.

We used Shallcross' Material and Energy Balance Concept Inventory (CI) to assess students' conceptual understanding of the material early in the semester and again late in the semester (Shallcross 2010). Shallcross' CI is a 22 multiple choice question instrument that assesses a student's understanding of basic material and energy balance principles. The instrument is designed to identify the misconceptions that students have when they start the course, some of which are deeply engrained and difficult to correct. We implemented these early and late CI tests in each of the 4 semesters studied. The early CI scores across the semesters were similar, as evidenced by the failure of ANOVA ($p = 0.712$) and Kruskal-Wallis ($p = 0.756$) tests to reject the hypothesis they had equivalent means. To test the hypothesis that the late CI scores were higher than the early CI scores, we conducted a paired t-test. The late CI scores were 3.98 points higher (out of 22 total points; $p < 0.0001$) with a 95% confidence interval of [3.45, 4.50]. See Figure 4 to see a plot of each student's paired CI scores. The points are jittered to make multiple observations of the same values visible. These results indicate that the PSS students' understanding of mass and energy balances concepts improved significantly over the course of a single semester.

To account for the fact that it is harder for students whose CI scores were high at the beginning of the semester to significantly improve their late CI score, we also calculated the normalized gain of the students' scores as follows (Hake, 1998):

$$\text{Normalized Gain of CI Total Score} = \frac{(\text{Late CI Score - Early CI Score})}{(22 - \text{Early CI Score})} * 100$$

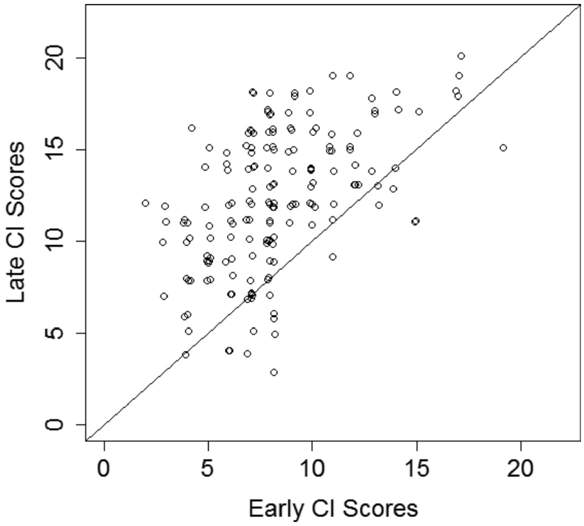

Figure 4. Late CI Scores vs Early CI Scores.

The distribution of these normalized gain scores are plotted in Figure 5, which shows that almost all of the students improved their CI scores. A normalized gain score of 14%, 29% and 47% was in the 25th, 50th, and 75th percentile, respectively. In addition, we tested the hypothesis that the mean Normalized Gain Total Score was greater than zero using a one-sided t-test, which returned a p-value of less than 0.0001 with a sample average of 27.68%.

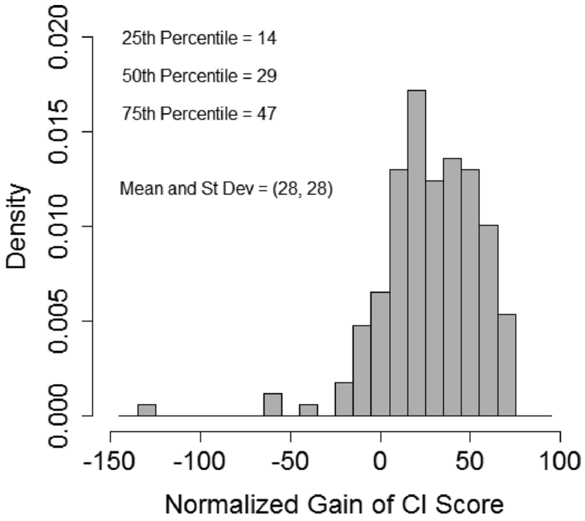

Figure 5. Histogram of Normalized Gain of CI Total Scores.

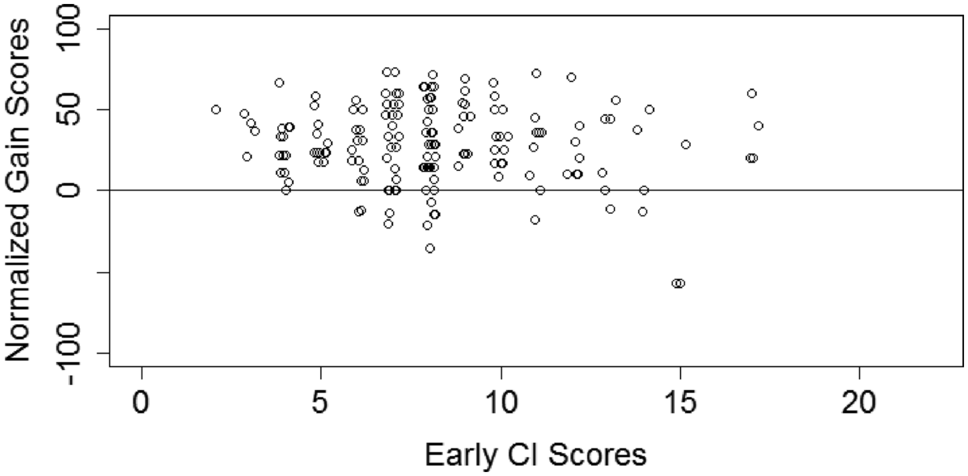

Figure 6. Normalized Gain Scores vs Early CI Scores.

We wondered if students who started with a better conceptual understanding were able to achieve more of their potential score increase than students who started with a lower score. To test this hypothesis, we plotted the Normalized Gain Scores against the Early CI Scores (Figure 6). We found no relationship between the Early CI Score and the Normalized Gain Scores. A linear regression on these variables failed to reject the slope coefficient was zero ($p = 0.18$). These findings suggest that no matter what level of conceptual understanding a student has when they start the course, they can achieve significant gains in conceptual understanding over the semester.

Finally, we analyzed each semester separately. Figure 7 plots the individual Late CI Scores versus Early CI Scores for each semester the study was conducted. We see that in each semester the majority of students' late CI scores were higher than their early CI scores (as indicated by the points that lie above the diagonal line that bisects the plot). These differences were statistically significant as indicated by paired t-tests whose p-values were in the range of 0.000005. These change scores were quite large for many students, which is indicated by the vertical distance from the diagonal line.

Taken together, these analyses show that PSS significantly improved our students' conceptual understanding of material and energy balances by providing them with a team-based apprenticeship studio environment that focused their attention on learning how to solve challenging analytical engineering problems.

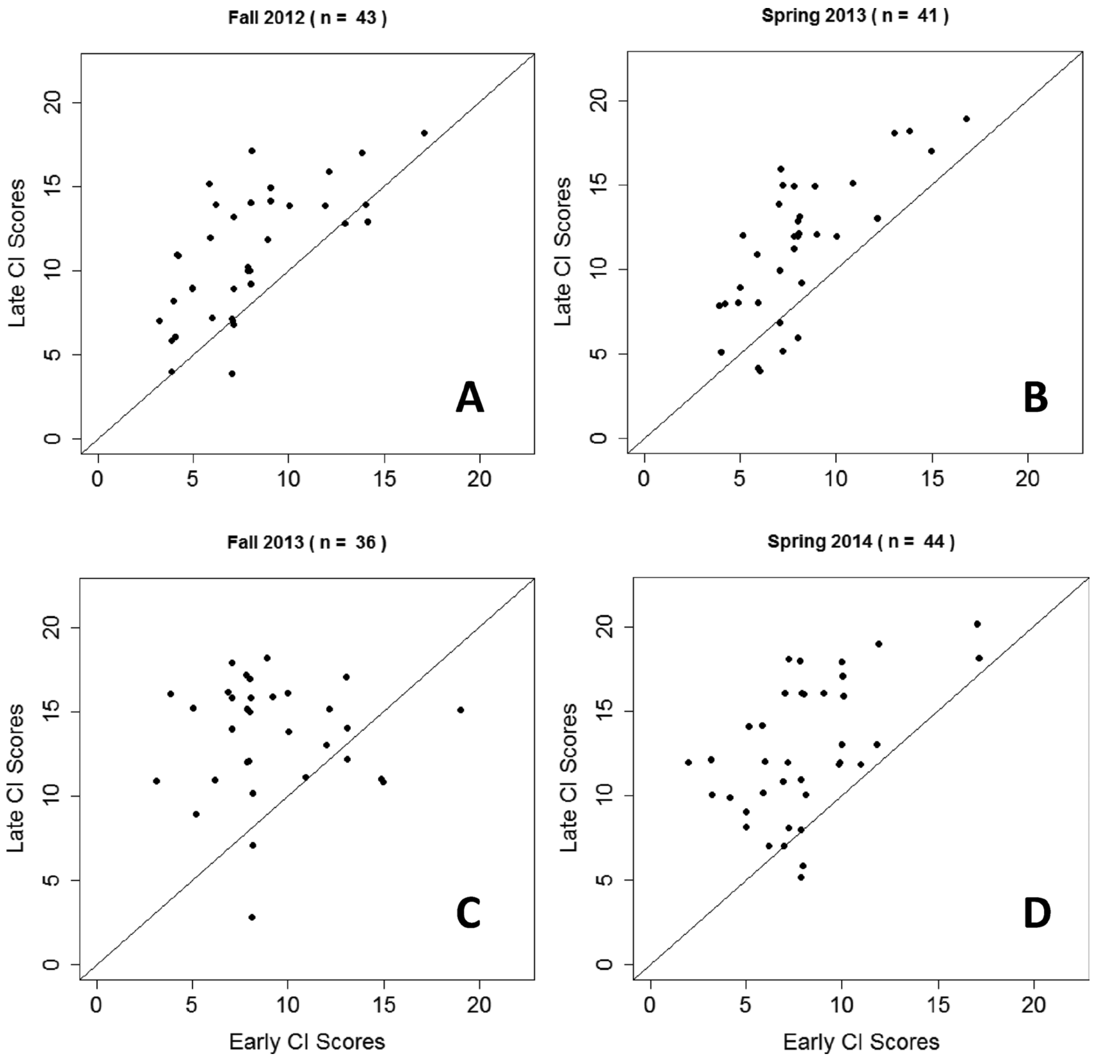

Figure 7. Late CI Scores versus Early CI Scores for Four Semesters.

SUMMARY AND CONCLUSIONS

This paper describes the development of a learning environment we call the *problem-solving studio (PSS)*. The PSS approach refers to a set of participant structures that govern how instructors spend classroom time with their students. The affordances of PSS make it possible for instructors to carry out dynamic scaffolding, which means they are able to modify the support they provide in real-time, as well as modify the difficulty level of the problems, to help ensure each student is challenged at a level that is beyond what they could accomplish on their own, but at the upper end of what they can accomplish in the PSS setting. Since concerns are sometimes raised that problem-solving does not facilitate growth in conceptual understanding, we studied the impact PSS had on students' conceptual understanding of material and energy balances when it was used to teach an entry-level biomedical engineering course on this topic (i.e., BMED 2210 at Georgia Tech). We used Shallcross' concept inventory of mass and energy balances to quantify the gains in conceptual understanding that PSS students' achieved (Shallcross 2010). The average score increase was 4 points out of 22, with a high level of statistical significance. We found the average normalized gain score was 28% and independent of the early CI score. The main implication of our findings is that learning environments that focus on developing students' problem solving skills can significantly enhance students' conceptual understanding of the material. We anticipate that instructors who decide to flip their courses will find the PSS approach useful as a way to structure the in-class time they have freed up by putting their lectures online.

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APPENDIX

Problem Statement	
Textbook problem statement: Consider a warm dry day with an air temperature of 28˚C and a relative humidity of 60% (i.e., has a moisture content of 0.014 g water vapor per g dry air). A person sitting on a park bench enjoying the beautiful spring day inhales at an average rate of 7 g dry air/min and exhales air saturated with water at body temperature (37˚C) and 1 atm. How much heat is this person losing by breathing? Report your answer in [kcal/hr]. A diagram of this system is depicted below and the heat capacity of dry air is 1.05 J/(g ˚C)	**PSS version of the problem:** How much energy do we lose per day by breathing? Report your answer in food calories per day.
Problem Structuredness	
The PSS problem is less well-structured because it leaves it to the problem solver to infer…	• the temperature and pressure of the exhaled air, which should be possible since most students at this level know that the normal core body temperature of humans is 37˚C and that the barometric pressure is usually close to 1 atmosphere • that the air inside the lungs is in contact with moist tissues long enough to become saturated with water vapor
The PSS problem is less well-structured because it has multiple viable solutions because…	• it does not prescribe for the problem solver how to model the inhaled or exhaled gases. Therefore, the problem solver could decide to model the incoming air under that day's weather conditions or under any other set of conditions. • the problem solver must decide how to model the composition of the exhaled air. Choices include solving the problem using realistic compositions of exhaled air that would include less oxygen and more carbon dioxide, or using the simplest possible model that treats the inhaled and exhaled gases as composed of water vapor and one non-condensable gas such as nitrogen.
Problem Complexity	

The PSS problem is more complex because…	• It requires the problem solver to have a greater breadth and depth of knowledge regarding human physiology and the chemistry of two-phase systems.
	• For example, the PSS version requires the problem solver to:
	  • know, or be able to estimate, the rate at which humans breathe and the average volume of each breath
	  • recognize that the exhaled gases will be saturated with water vapor, and then be able to calculate how much of the exhaled gas is water vapor and how much of it is other gases

Table 4. An illustration of how PSS problems are less structured and more complex.