Problem-Based Learning to Promote Student Creativity

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Abstract

The authors investigate the effectiveness of problem-based learning to promote creative thinking in a classroom setting. Three problem-based learning exercises were given to students to encourage them to practice their creative-thinking skills as part of a graduate course in engineering management.

The first exercise asked the students to develop a team-based process that would allow them to perfectly sort a set of six decks of highly shuffled playing cards as quickly as possible. Direct observation of time trial results through three generations of process design allowed direct observation of significant improvement in team performance. The second exercise required the students to design a mailroom system for a medium-sized company, with a focus on accurate and efficient mail delivery. Students were encouraged to question assumptions, eliminate unnecessary overhead tasks, and optimize the critical path of the mail delivery process. Again, direct observation of simulated mail delivery results demonstrated significant improvement in team performance throughout the activity. Finally, students were asked to tackle a real-world problem by working with each of the two co-teachers to suggest creative new directions for research projects associated with the faculty members' research areas: virtual reality and nanotechnology. The students were able to develop several very interesting suggestions that are being evaluated for future research work and potential publication.

Assessments of self-efficacy in a variety of creativity domains were performed by the students before the first exercise, after each of the three exercises, and at the end of the course. The results of these assessment efforts demonstrated a statistically significant improvement in students' perception of their own creativity throughout the three-week duration of the study. The average self-efficacy score increased after each of the three problem-based learning activities, suggesting that the beneficial effect of successive problem-based learning experiences is at least partially cumulative.

1. Introduction

Engineering is a discipline that requires many skills, including knowledge of mathematics and science, expertise in engineering analysis and design, and excellent communication and teamwork skills. Over the past decade, it has become increasingly apparent that an ability to think creatively is an essential tool for an engineer. Perhaps, this need for creativity is best encapsulated by the National Academies of Engineering in their report The Engineer of 2020:

> "Creativity (invention, innovation, thinking outside the box, art) is an indispensable quality for engineering, and given the growing scope of the challenges ahead and the complexity and diversity of the technologies of the 21st century, creativity will grow in importance. The creativity requisite for engineering will change only in the sense that the

> problems to be solved may require synthesis of a broader range of interdisciplinary knowledge and a greater focus on systemic constructs and outcomes."[1]

In spite of this need, it has proven very difficult to teach creativity in a classroom setting. It is essential for engineering educators to perform rigorous research to determine the methods that can promote creative thinking in their students. In this paper, we demonstrate evidence that problem-based learning is one effective method for doing so.

2. Problem-Based Learning

Problem-based learning (PBL) is an educational method in which students "learn through facilitated problem solving."[2] PBL methods provide students an opportunity to solve "a complex problem that does not have a single correct answer,"[2] which is an excellent description for nearly all engineering problems. The role of the teacher (known here as a "tutor") during a PBL session is to facilitate the learning process and provide students with specific resources they request, rather than structuring the problem and providing students with all needed knowledge.[3]

Problem-Based Learning exhibits six characteristics that differentiate it from more traditional, lecture-based educational experiences:

1. Learning is student-centered, rather than teacher-centered.
2. Learning is done in small student groups, ideally 6-10 people.
3. Facilitators or tutors guide the students rather than teach them.
4. A problem forms the basis for the organized focus of the group and stimulates learning.
5. The problem is a vehicle for the development of problem solving skills. It stimulates the cognitive process.
6. New knowledge is obtained through Self-Directed Learning.[4]

Advocates of Problem-Based Learning believe it can be used to convey content subject matter while also enhancing such important skills as communication, problem-solving, critical thinking, collaboration, and self-directed learning.[5,6] Evidence has also been presented that PBL methods narrow the achievement gap in middle school science for African-Americans.[7]

Some research on PBL methods has indicated that they are most effective once students have developed a certain level of competency within a field, and they may place a heavy cognitive load on the learners if they are introduced too early in a student's learning experience.[8]

Some work has also been performed to study the link between Problem-Based Learning and creativity. Since creativity is often expressed within the context of solving a problem, PBL seems like a logical tool to be used to help instill creativity within students.[9] This research has demonstrated that PBL methods can also be used to instill in students the ability to develop insights, intuition and inventive thinking skills.[9]

Although it is apparent that a great deal of educational research has been performed to study the effectiveness of PBL, it has not been demonstrated that PBL can promote creativity within an engineering context. Since engineering creativity is very different than the sort of creativity required by other subjects, it will be beneficial to test the effectiveness of PBL to promote creativity within an engineering context.

In addition, previous research tends to focus on either (1) a single PBL activity placed within the context of a traditional lecture class, or (2) learning experiences composed entirely of PBL activities. In this paper, the focus will be on a series of three PBL activities, one week apart from each other, which are intended to reinforce and strengthen the smaller-scale active learning exercises and traditional classroom experiences that surround them. Performing the study in this manner will determine whether repeated PBL activities reinforce each other, or whether a single PBL session would be just as effective.

3. MEM 705: Creativity and Innovation

The authors have team-taught a course to graduate students in the Master of Engineering Management program each of the past three summers. This course is designed to teach students the importance of creativity and innovation, to demonstrate tools to promote open thinking, and to demonstrate the importance of creativity and innovation in business and industry. The course meets seven times, each for a 220-minute period with two 10-minute breaks. The course learning objectives are as follows:

- Explain the fundamentals of creativity
- Generate creative ideas for new products, services, and processes
- Demonstrate an understanding of creativity techniques and tools
- Describe how ideas are refined and developed
- Manage an idea through the development process

Early course subjects focus on the importance of creativity and individual creativity tools. Subjects in the middle of the course then introduce team creativity tools and practice, as well as how to create a workplace environment that fosters innovation among employees. Subjects later in the course focus on managing innovation and the financial gain associated with companies who are successful in creativity and innovation. The title and subject of each lesson are shown below:

1. Foundations of Creativity and Innovation
2. Maximizing Your Personal Creativity
3. Building a Creative Culture
4. Improving Your Ideas: Steel Sharpens Steel
5. Creativity in Practice
6. Turning Ideas into Cash
7. Internalizing Creativity and Innovation

Assignments for the course are split between two categories: written vs. oral and individual vs. group. There are five short individual writing assignments, three team presentations, and a final team paper. The team-based assignments build on one another, such that students first generate many ideas as a solution to a particular problem, then refine those ideas, and finally present an optimal solution to their problem. In the first two instantiations of the class, individuals also read a book of their choosing on the subject and then completed both a written summary and an oral presentation summarizing their chosen book.

Assigned readings for the course include *The Creative Habit* by Twyla Tharp, *Innovation to the Core* by Peter Skarzynski and Rowan Gibson for every instance of the course, and the book *The Innovator's Toolkit* by David Silverstein, Philip Samuel, and Neil DeCarlo in the first year and *Thinkertoys* by Michael Michalko in years two and three.

To reflect the course's focus on creativity and innovation, the authors try to avoid using lecture as a primary teaching method, instead spending as much time as possible using active learning to help the students understand the principles to be learned. Further, with two instructors, each night is balanced by an interleaving of the facilitators for the topics for the evening. Each course session starts out with a creativity exercise. Delivery of content topics usually starts with a brief presentation by the facilitator for that topic, followed by an in-class exercise based directly on that topic. In the early part of the course, this typically consists of describing a creativity technique, followed by an in-class example putting that technique into practice.

4. Applying Problem-Based Learning to Develop Creativity

In Summer 2012, the authors modified the last three weeks of the course described in the previous section to include three different PBL exercises. In each case, a significant block of time (one to two hours) was set aside to perform each PBL exercise, and these exercises were the focal points of the last three weeks of the course. They were intentionally placed toward the end of the course in order to align with the research (presented in section 2) indicating that PBL activities are most effective once students have developed at least a minimal level of experience with a subject.

In each of the three PBL activities, faculty served only as coaches or mentors, helping to ensure that students fully engaged with the problem and understood the parameters of the problem, but providing no technical help as the students grappled with its complexities.
The three problems presented to students were:

1. A **card-sorting problem**, in which students had to perfectly sort and order four different decks of cards that had been very thoroughly mixed together. The goal of this exercise was to complete the sorting as quickly as possible and without errors. This problem was presented in the context of a competition between two teams of four students, each coached by one of the two team-teaching faculty.
2. A **mailroom problem**, in which students were asked to design a mail sorting and delivery process for a small 200-employee company with 12 departments located in four buildings. In this case, all students worked collaboratively to solve the problem and implement their process together.
3. A **research directions problem**, in which students were given a briefing on each of the two faculty member's research efforts (one in virtual reality and the other in nanotechnology), and they were then asked to suggest new problems that might be future research directions for each field. Although this problem was at a much higher level than the other two, it also had the advantage of being a real-world problem in which the results could impact the actual direction of a scientific research effort.

Each of these PBL exercises is described in more detail in the following three sections.

4.1. The Card-Sorting Problem

The first problem focused on students developing their creativity in optimizing a process involving parallel workers. Students had to use either five or seven team members in order to sort six decks of cards into a precisely specified order and then place each deck in the correct box. The six decks were distinguishable, but similar, and all cards were thoroughly mixed together in a large box. The six decks consisted of:

1. Blue back, elaborate pattern, small print
2. Red back, elaborate pattern, small print
3. Blue back, plain pattern, small print
4. Red back, plain pattern, small print
5. Blue back, elaborate pattern, large print
6. Red back, elaborate pattern, large print

The mix of these six decks was meant to add complication to the problem. In addition, there were never six team members, so that the number of members would be different from the number of decks. These constraints were all by design in order to provide as many dimensions of innovation as possible.

Students had a 60-minute block to develop their strategy and then practice and refine their sorting strategy. They were divided into two groups and placed in separate rooms to limit inter-group communication without sacrificing communication within each group. In general, student groups were able to practice the sorting procedure three times before moving on to the competition stage. Figure 1 shows students engaged in the card-sorting activity.

Figure 1. Students practice their algorithm for the card-sorting problem.

The two teams then entered a competition phase during which both teams (now in the same room) raced to complete the task first. This was followed by an opportunity to revise their sorting strategy, and the exercise ended with a second competition round. After the exercise, the facilitators led a discussion asking each team to describe their method and any creativity tools they used to develop the method. After each team had described their algorithms, a final creativity exercise was to come up with a melded method that would optimize the task using ideas from both groups.

4.2. The Mailroom Problem

The second PBL activity presented to the students was an opportunity to design a mailroom system for a medium-sized company with 200 employees. This imaginary company owns four buildings, and a total of 12 departments are shared unevenly among those four buildings. The instructors prepared in-boxes and out-boxes for each of the 12 departments, and it was the students' responsibility to design an efficient system to deliver letters from the out-boxes of the originating department to the in-boxes of the destination department. Furthermore, each "letter" (represented by a quarter-page piece of paper with the name of the recipient), had to undergo a restrictive seven-step process before it could be delivered. The instructions provided to students are shown below:

1. Write the employee ID number of the recipient in the top left corner of the envelope. This information is provided to you sorted by ID number in list #1.
2. Another employee should double-check the employee ID number and place a check mark next to it when it is verified.
3. Record the ID number of the recipient on a master list of delivered mail.
4. If the recipient's ID number is less than 100,000, neatly circle the ID number. This will allow the mailroom to know that the letter is addressed to a company VIP and should be handled carefully and delivered quickly.
5. Add the recipient's department name in the top right corner of the envelope. This information is provided to you sorted by department on list #2.
6. Add the building for the recipient's department in the bottom right corner of the envelope. This information is provided to you sorted by department on list #3.
7. Deliver the envelope to the recipient's departmental mailbox, which will be located in the corner of the room corresponding to that department's building.

Clearly, students were initially provided with the information in a highly unoptimized format, requiring them to first look up the recipient's ID number on one unalphabetized list, then to look up the recipient's department in another list sorted by department, and then finally to look up the building for that department in a third list. In addition, many of the instructions given above were intentionally written to add very little value, such as looking up, double-checking, and recording the recipient's ID number, as well as indicating which mail should be given VIP treatment. These unnecessary requirements were included in the initial process in order to give the students an opportunity to identify and remove them, optimizing the process.

The students first performed the activity as given, and they were highly frustrated by the entirely inefficient process. In the second trial, they were asked to try to optimize it without changing any of the success criteria. In the third trial, they were given the opportunity to request modified and combined lists, and their only success criterion was to deliver the mail as quickly as possible. As expected, the students requested a sorted, condensed, and optimized list of employees including only last name, department, and building number. They also eliminated the use of ID numbers entirely, and since all mail was being delivered so efficiently, it was no longer necessary to provide special service to VIP letters. After making these changes, students were able to increase the mail throughput by more than a factor of ten, and they found that not only was the work more efficient, it was also more pleasant.

4.3. The Research Direction Problem

The goal for the third problem was to present a real-world example to the student in the hopes of increasing motivation and interest in the activity. Since both instructors are active researchers in their fields of expertise, it was decided that each instructor would give a summary of a research topic, present challenges, and then ask students to use creativity tools in order to address the challenge or come up with new ways of tackling the problem. The students were also asked to identify new areas in which the existing solutions could be applied.

The first research area presented was nanotechnology, specifically the design of quantum-dot cellular automata (QCA) circuits for quantum computing. Students were given a 17-slide talk giving background information, detailing present progress in the field, and finally presenting areas for future work and challenges. The presentation started with an introduction to nanotechnology, then worked through basic QCA geometry in order to build basic components such as wires, AND gates, and OR gates. The instructor showed how these basic components could be used to make more complicated circuits such as adders and arithmetic logic units and ended by showing the present-level state-of-the-art devices such as crossbar switches and programmable arrays of logic. The presentation ended by posing the following questions to the students:

- What is a problem that could be solved using this new technology?
- What is a feature of this technology that could be modified?

Students presented many ideas that neither instructor had considered, as well as asking basic questions about the premise of the research that provided a fresh perspective on the area of study.

The second area of research presented was virtual reality applications in undergraduate education. Students viewed a short video as well as listening to the second instructor present information detailing virtual reality technology, present hardware capabilities, applications that have already been developed, current challenges, and proposed future applications. Students were then asked:

- What possible other areas of education could this technology be applied to?
- How can the current challenges be addressed?
- What other modes of presentation could these applications be presented on?

Students were asked to use the “think, pair, share” creativity method to come up with ideas on their own, discuss their ideas with a friend, then present them to the group. Of the twelve ideas presented for new applications, five were thought by the instructor to have significant merit and had not previously been considered. In addition, discussion presented several fresh perspectives for the application of the technology to not only education, but to fields such as communication, training, and entertainment.

5. Outcome Assessment and Statistical Analysis of Results

In order to demonstrate that the activities described above effectively helped students to become more creative, it is necessary to perform a detailed outcome assessment and statistical analysis of students’ self-assessments of their self-efficacy as well as direct measurement of their actual performance on the problems being studied.

Prior to the beginning of the first PBL activity, students were asked to answer the following three questions in a pre-test survey:

1. To what extent do you believe that you are able to apply creativity to solve problems?
2. To what extent do you believe you are able to develop innovative solutions to improve a product?
3. To what extent do you believe you are able to develop innovative solutions to improve a process?

The possible responses in a Likert-type scale were “Very much (5),” “Quite a bit (4),” “Somewhat (3),” “A little bit (2),” and “Not at all (1).” The pre-test was given during the fifth class meeting (out of only seven four-hour class meetings), and so it was anticipated that the students would report relatively high self-efficacy on these questions. Nonetheless, in spite of significant reading assignments and extensive explanation and small-scale demonstration of many creativity tools, the average response on each of these three questions was only 3.00/5.00 (corresponding precisely to “Somewhat”).

After each of the three PBL activities, students were given precisely the same three questions, with three other questions added. The three new questions were specific to the PBL activity they had just completed:

4. To what extend did [activity] contribute to your ability to solve problems creatively and to develop innovative ideas?
5. Was [activity] fun?
6. Was [activity] a worthwhile use of class time?

Table 1 shows the results of the first three (self-efficacy) questions for each of the four survey implementations.

Table 1. Average Response on Self-Efficacy Survey Questions

	Pre-Test	Post-Test #1	Post-Test #2	Post-Test #3
Solve Problems	3.00	3.75	3.63	4.13
Improve a product	3.00	3.25	3.50	3.75
Improve a process	3.00	3.38	3.75	4.00
Average	**3.00**	**3.46**	**3.63**	**3.96**

Figure 2 illustrates the average of these three self-efficacy questions over each of the four survey implementations. It is apparent that the average student self-efficacy score increased with each new PBL activity and that the beneficial result of these activities appears to be cumulative.

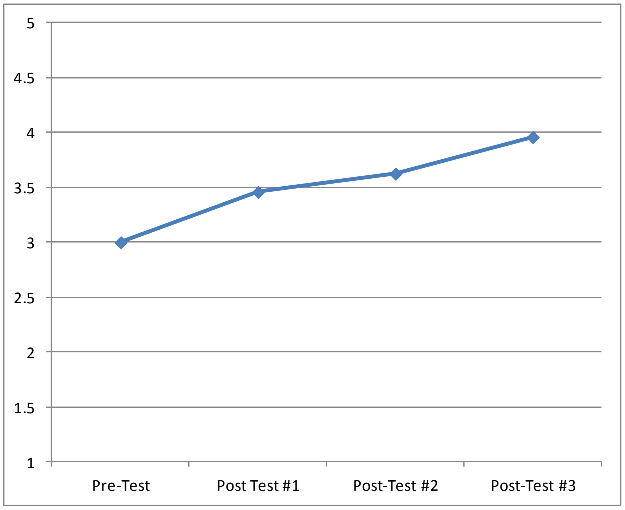

Figure 2. Average self-efficacy score after each PBL activity.

Although these data are compelling, they represent a relatively small sample size (N=8). Therefore, it is important to perform a statistical analysis of the results in order to determine whether there is a statistically significant effect or whether the observed results can be attributed to sampling variation. The authors performed a two-sample t-test for the difference between the means of each question between each of the three post-tests when compared to the pre-test. The p-values from each of these 12 comparisons are shown below in Table 2.

Table 2. P-value for difference between pre-test and post-tests

	Pre-Test to Post-Test #1	Pre-Test to Post-Test #2	Pre-Test to Post-Test #3
Solve Problems	0.089	0.144	0.018
Improve a product	0.296	0.169	0.031
Improve a process	0.216	0.046	0.010
Average	**0.146**	**0.086**	**0.008**

The p-value represents the likelihood of measuring a result at least as unlikely as the one observed if there is no difference between the samples. A p-value less than 0.05 is widely considered to be an appropriate threshold to demonstrate a significant result. Cells that meet this threshold in Table 2 are highlighted. As these cells illustrate, the “Improve a process” question attains statistical significance after the second activity, while all three questions (and the average) attain statistical significance after the third question. Since all three activities (and especially the first two) focus primarily on improving a process, it is not surprising that this question would provide the most positive result.

The results of the other three (descriptive) survey questions are shown in Figure 3.

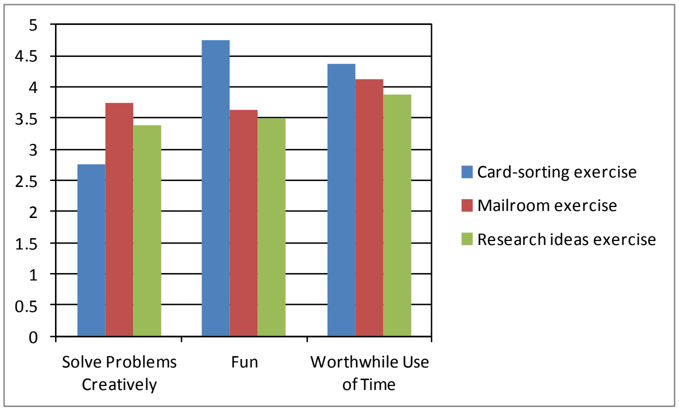

Figure 3. Student responses to descriptive survey questions.

As this figure shows, students did not seem to perceive that the activities were being highly beneficial to them at the time they were being performed, although their self-efficacy results from the previous figure illustrate that at the same time students' confidence levels were improving. It is especially interesting to note that the activity that the students (and faculty) considered to be the most fun (the card-sorting activity) was also the one that rated the lowest in terms of students' perception that it contributed to their ability to solve problems creatively.

It is possible that students have been trained to believe that anything that is fun cannot have significant educational value. If this is the case, then PBL provides an even greater learning tool than previously believed, because it will help students to learn without them being specifically aware that they are learning.

All three activities were considered by students to be a worthwhile use of classroom time. Students were also asked on the final course survey (at the end of class meeting #7) to indicate the degree to which each of these activities "contributed to the achievement of the learning objectives." The results of these questions are shown in Table 3.

Table 3. Contribution to Course Learning Objectives

Card-sorting exercise	4.286
Mailroom exercise	3.857
Research ideas exercise	3.857

Very interestingly, students' perceptions of all three activities (and especially the card-sorting activity) were significantly improved by hindsight. Although the questions are not identical, there is significant overlap between the course learning objectives and the content of question #4 on the post-test ("…solve problems creatively and to develop innovative ideas"). Student responses to this question increased for all three questions, and most notably they increased from 2.75 to 4.286 for the first activity. It appears that students may need some time to process the benefit obtained by a PBL activity in order to recognize its full worth to their education.

Finally, it is important to directly measure students' performance on creativity exercises in order to determine whether their performance is actually improving. Figure 4 illustrates the average time each team of four students required to complete the card-sorting activity through each of the five trials that were completed. As this figure illustrates, performance improved significantly for both teams. The final trial required just 52% of the initial time for Team #1 and just 58% of the initial time for Team #2.

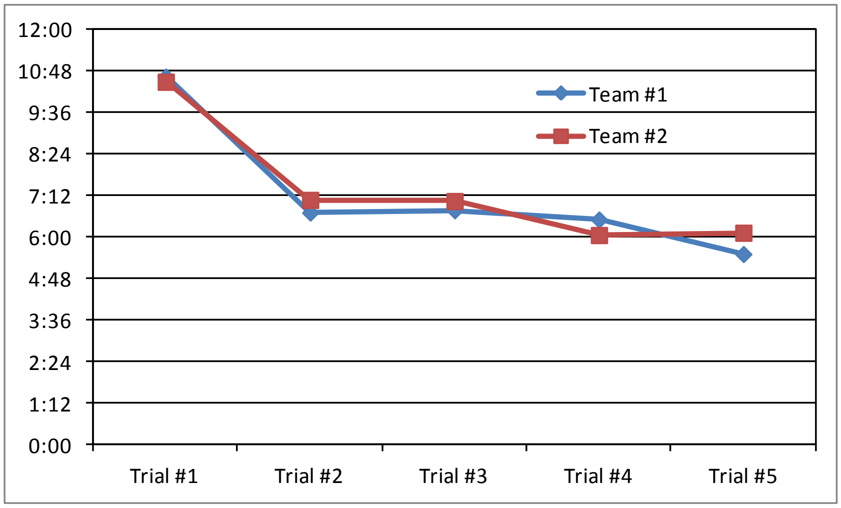

Figure 4. Time required for each team and trial on card-sorting activity.

These results demonstrate that not only do students believe that they are able to apply creativity to solve a problem, their performance on those problems also confirms the effectiveness of PBL activities to promote creativity.

6. Conclusions

Creativity is a difficult skill to impart to students, but the results demonstrated here have shown that a problem-based learning approach can be effective in an engineering context. Even after a single exercise, students recognized that their own ability to creatively solve problems had increased. Further, we show that multiple applications of this technique can be effective and that students gain extra skill with each successive application. After the third exercise, students rated their ability in all three areas higher than in the pre-test at a statistically significant level. Finally, students' perceptions of the value of problem-based learning may be delayed, as they may not immediately see the benefit of exercises. With hindsight, students seem to appreciate the value of such exercises, along with their corresponding perception of their own improvements in ability.

Bibliography

1. *The Engineer of 2020: Visions of Engineering in the New Century*, Washington, D.C.: The National Academies Press, 2004, 118 pp.
2. C. E. Hmelo-Silver. “Problem-Based Learning: What and How Do Students Learn?” *Educational Psychology Review* **16** (3): 235–266.
3. H. Schmidt, G. Rotgans, and E. Yew. "The Process of Problem-Based Learning: What Works and Why.” *Medical Education* **45** (8): 792–806.
4. H. Barrows. “Problem-based learning in medicine and beyond: A brief overview.” *New Directions for Teaching and Learning* **1996** (68): 3–12.

5. T. Barrett. “The problem-based learning process as finding and being in flow.” *Innovations in Education and Teaching International* **47** (2): 165–174.
6. S. H. Wells, P. J. Warelow, and K. L. Jackson. “Problem based learning (PBL): A conundrum.” *Contemporary Nurse* 33(2): 191–201.
7. C. E. Hmelo-Silver, R. G. Duncan, and C. A. Chinn. “Scaffolding and Achievement in Problem-Based and Inquiry Learning: A Response to Kirschner, Sweller, and Clark.” *Educational Psychologist* **42** (2): 99–107.
8. J. Sweller. “Cognitive load during problem solving: Effects on learning.” *Cognitive Science* **12** (2): 257–285.
9. O. Tan, *Problem-based Learning and Creativity,* Cengage Learning Asia, 2008, 264 pp.

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