Special Session: Learning and Practice of Engineering Fundamental Principles for Long-Term Retention

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***Abstract*—This special session is an interactive experience for engineering educators to participate in learning activities for review and retention of engineering fundamental principles. It can often be a struggle to get students to recall concepts from previous courses, such as foundational physics and mathematical theory. Session leaders will describe how students learn and apply the fundamental principles in an integrated electrical, mechanical, and industrial engineering program with an entrepreneurial mindset. The use of active and collaborative learning techniques in this program make the newly acquired knowledge "sticky," so it is long-lasting and retrievable in the future. Participants will leave with resources to consider how they may incorporate these activities into their courses.**

I. Goal of Session

As we develop students into engineers, they need to be able to recall various engineering concepts, see how they are related, and to apply them to solve open-ended problems. Often engineering concepts are taught with little or no relation to other theories, especially if it is not in the same topic area so it can seem very disjointed and confusing for students. A concept learned in the first semester of the freshman year will often be forgotten by the time they graduate four years later, especially if the student was only exposed to the topic once. As engineering educators, we need to build context into our teaching and set up intentional activities for interleaved space retrieval, so we get students to practice what will be examined later on, in very similar situations. Traditional teaching methods are often unengaging for certain types of students. In recent years, the use of active learning strategies has been on the rise. Recent research suggests that these strategies can lead to improvements in learner engagement, problem-solving skills, and long-term retention of knowledge.

The specific goals of this session are to:

1) present an overview of recent research of active learning science.
2) describe fundamental principles of engineering in program context.
3) engage participants in three learning activities.
4) facilitate participants to discuss using these activities in their courses.
5) involve participants in determining collaboration ideas for the future.

II. Theoretical Foundation and Related Work

Recent research on learning science indicates that the process of learning is essential. In his 2017 book titled "Learn Better," Ulrich Boser suggests that the learning process itself is perhaps the most important predictor of learning success [1] and cites a recent meta-analysis as support for this claim [2]. Effective learning is an activity, in which the learner actively participates in a dedicated and engaged process. Boser's recent research shows that people learn more when they are praised for their effort rather than for their intelligence [1]. Other important aspects of effective learning include recognizing value, motivation, self-efficacy, targeted learning, developing and extending learning, making connections, relating knowledge to other domains, and re-thinking the knowledge acquisition process. Boser cites many studies that indicate that active and self-directed learning in an enjoyable manner is highly useful for long-term storage of knowledge and can result in an enhanced ability to recall that knowledge in the future when it is needed again.

Self-quizzing and self-explaining are examples of more mentally engaging learning activities; those that require struggle and exert more mental effort are superior to other passive learning methods such as listening, highlighting text, and similar traditional learning methods in university settings [1]. Boser goes on to discuss learning by self-explaining and suggests that by explaining an idea to ourselves, we make meaning of the knowledge and connect the concept to other knowledge, which results in deeper, more lasting learning. He writes that researcher Dylan Wiliam argues that more active forms of learning are effective when people are thinking hard and thinking hard about knowledge [1], [3]. Making sense of new knowledge and connecting it to other concepts is another important aspect of effective learning. Boser suggests using flashcards, practicing self-quizzing and interleaved spaced retrieval as effective learning activities to build long-term retention of new knowledge. People need to practice learning strategies, to receive feedback, and to explain knowledge to themselves and others [1]. Even monitoring performance and self-assessing confidence levels can improve learning.

People forget at varying rates, based on many factors. In his meta-analysis "How Much do People Forget?", which covered

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14 research studies, 69 conditions, and over 1000 learners, W. Thalheimer found that learning methods matter and learning interventions, such as spaced retrieval, can have profound positive effects on forgetting less quickly [4]. Spacing the learning out appropriately can be a useful learning technique. Spaced training, rather than cramming, leads to more robust memory formation, per Smolen, Zhang, and Byrne [5].

Learning by doing is also a highly effective learning process, per John Dunlosky and colleagues [6]. Kolb's experiential learning model includes learning by doing as an important stage in the learning process [7]. Engineering education specialist John Heywood writes about several related concepts that improve learning including motivation, emotions, flow, a sense of autonomy, and faculty expectations - all of which can be used to enhance deep learning [8]. A sense of autonomy and intrinsic motivation to promote deep learning is helpful [8] and connecting positive emotions to learning can also have strong positive effects [9]. Culver and Yokomoto [10] write that "by designing our courses to provide an appropriate level of challenge, with multiple paths to learning material and continual feedback to monitor performance, we can assist students in achieving optimum academic performance," also cited by Heywood [8].

The learning space also impacts the effectiveness of learning. Recent research on the physical learning environment indicates that the physical learning space has a statistically significant impact on student engagement in learning activities [11]. Felder and Silverman suggest that pairing visual pictures and verbal descriptions is a powerfully effective learning strategy, and they recommend using active learning paired with reflection to boost impact [12].

Recently, research on gamification shows positive effects on learning. In the book, "The Gamification of Learning and Instruction" [13], Karl Kapp describes gamification as activities that use game-like or fun elements to promote learning and engagement. Engaging players in a challenging, somewhat abstract game-like system, guided by clear rules and the opportunity to win comprises a "game." Including interactivity, feedback, and emotional reaction complete the "game" elements. Structural gamification is the application of game elements to motivate learners to go through the content and to engage them in the process of learning through rewards. The most common form of rewards are points, badges, achievements, and levels and only one of these elements of a game are needed to engage a person. It also encourages the learner to return to the material on a regular basis [13].

The authors and their colleagues have integrated many recommendations from learning science, as outlined above, to create active, engaging learning activities that promote deep, long-lasting learning. Specifically, we relate examples of the learning activities that we use to facilitate student engineers' process of learning the fundamental principles of engineering. The next section describes the context of our program, followed by descriptions of the learning activities themselves.

III. Program Context

The Iron Range Engineering (IRE) program is an upper-level undergraduate engineering education program of Minnesota State University, Mankato located in northern Minnesota. It is ABET accredited and received the 2017 ABET Innovation Award. The program began in 2010 and is modeled after the project-based learning (PBL) engineering program at Aalborg University in Denmark [14]. Project-based learning is a form of active learning in which large-scale projects provide context for technical learning. The IRE program emphasizes continuous improvement and the development of self-regulated learning abilities, professional skills, and technical engineering knowledge, which is acquired primarily in one-credit courses called "competencies" [15]. Students learn technical topics through formal "learning conversations" as well as independent study with advising from faculty, affiliated instructors, and peers. Many learning conversations are flipped, so students learn the material outside of class meeting time. The in-class time is used to ask questions, discuss with peers, apply the new knowledge to their industry projects, and do other active and collaborative learning techniques to make the newly acquired knowledge "sticky," so it is long-lasting and retrievable in the future.

At IRE, the learning of technical material in each technical competency is focused around 4-5 fundamental principles. These principles are usually scientific laws or rules that form the base knowledge of a specific content area. Typically other related competencies will use these fundamental principles or build on that knowledge in more advanced topics. For example, in the Thermodynamics competency, the principles focused on are the 1st law of Thermodynamics, the 2nd law of Thermodynamics, Conservation of Mass and Property Relationships. The Heat Transfer competency also has the 1st Law of Thermodynamics as one of its fundamental principles along with the principles of Fourier's Law of Conduction, Newton's Law of Cooling and the Stefan-Boltzmann Law.

One way the authors and their colleagues focus the teaching of these fundamental concepts is through the use of a concept description or "describe sheet." The describe sheet structures the knowledge needed for each principle into six areas which include: word description, sketch/drawing, equation with units, engineering application, why does this matter in the real world and connections to other technical learning.

At the conclusion of each technical competency, students complete an oral exam where they are asked to explain aspects of the fundamental principles learned and solve close-ended problems related to those principles. Also, at the end of each of their four semesters at IRE, each student participates in a fundamental principles oral exam. During this exam, the students are tested on their knowledge of the fundamental principles they acquire as they complete their technical competencies. The exams are conducted in front of a panel, generally, two faculty members where various aspects of the "describe sheet" for many different principles are asked.

To help students practice and prepare for those oral exams, faculty regularly integrate various recall and retention activities into their learning conversations. It allows students to practice speaking and writing the principles individually, to their peers, and to faculty while obtaining feedback during the process on what to improve. Gamification activities in the form of game-based interactive on-line quizzing platforms such as Plickers [16] or Kahoot [17] and hands-on activities including the Pail of Principles and Escape Room, which are discussed in more detail in a later section, are also used.

These and other regularly spaced retention and application activities prepare students to synthesize and apply the principles in structured open-ended problems (as an oral exam each semester) as well as to solve design problems for clients in this project-based learning program. Blooms' higher order thinking skills are needed to accomplish the objectives of project-based learning, and structuring regular active review of fundamental principles of engineering improves outcomes in solving open-ended problems for IRE's industry partners.

Limited data was collected thus far because our program has less than 50 students in upper division, so the sample size is automatically small. We plan to track the use of these retention activities longitudinally to reach meaningful conclusions. For the escape room data collected during the 2017-2018 academic year, there was an average of a 4.6% increase in a student's fundamental principle exam score if they participated in the escape room both semesters. Students' confidence levels were also noted by the "check-in" faculty member, who asked each student how confident they were in describing the fundamental principles of engineering, both before and immediately after the Escape Room activity. Overall, 44% of students self-reported higher levels of confidence after the Escape Room activity. Some student feedback on these activities during the 2017-2018 academic year include:

- "Awesome way to study before exams."
- "Exciting game with in-depth test on knowledge"
- "Reminded me of principles I don't know yet."
- "New, different, put a little pressure on us. I have further identified & verified strengths vs. weaknesses. Nice job, faculty."
- "Made learning fun, exciting, and highly competitive. Makes you think on your feet. Highly focused. Would be fun to try again."
- "Engaging and challenging. Feedback was key and present. More feedback when people get things wrong."
- "Fun way to start studying for fundamental principles. I don't know if I learned anything new but I was able to recall."
- "Allowed me to practice interleaved spaced retrieval."

IV. Explanation of interaction

In this session, participants will be guided through a set of active learning techniques to practice the fundamental principles of engineering deliberately. The engineering concepts are reviewed in a fun, collaborative environment that range from minimal preparation to more in-depth longer-term events. Participants will complete a describe sheet for a fundamental principle of science, do the Pail of Principles activity in pairs, play a kinesthetic Escape Room game, and hear about other interleaved spaced retrieval techniques used at the Iron Range Engineering program to increase students ability to recall and apply fundamental principle knowledge long after its initial introduction.

V. Description of session

Participants will alternate between doing a learning activity, alone or in pairs, with a small group discussion on the applicability of the activity in their learning environment. Specifically, the session will be organized as follows:

1) A brief discussion on student retention of concepts and why as engineering educators we need to build context into our teaching for retention, retrieval, and application of engineering principles. (5 min)
2) *Activity*: Complete a describe sheet used in the Iron Range Engineering program. Each person will complete part of a describe sheet for a simple concept. The activity will start with individual work but turn collaborative. (5 min)
3) Discuss the purpose of describe and concept relation sheets. (5 min)
4) Discuss fundamental principles and Iron Range Engineering programs fundamental principles exam. (5 min)
5) *Activity*: Experience the Pail of Principles Activity in pairs. The fundamental principles and/or sample exam questions from the course are printed on slips of paper and kept in a plastic pail. Each pair draws a slip of paper and moves to a whiteboard. One person is the student, and one is the examiner. The student answers the question, using the whiteboard to illustrate the concept. After 2 minutes, they discuss the solution/answer presented, and examiner provides feedback. The pair then goes back to the Pail of Principles, draws another concept out of the pail, switches roles, and repeats the process. (10 min)
6) Debrief on the Pail of Principles activity. (5 min)
7) *Activity*: Escape Room Activity which will be an individual learning activity. Different fundamental principles are hung around the room. After making an origami dice, the participant will pick a principle they want to master. They roll the dice, and complete that part of the describe sheet, as indicated by the dice result, on the whiteboard. Once they think they have the correct answer, they will raise their hand, and an instructor will come by and assess. If the answer is correct, the participant gets a token; if it is not correct, the participant receives one more attempt at the same principle. To escape the room, the participant must acquire a certain number of tokens. (25 mins)
8) Debrief on the Escape Room activity. (5 min)
9) Other classroom methods to practice interleaved spaced retrieval. (5 min)
10) Time for reflection and answer questions. (5 min)

VI. Expected outcomes and future work

Engineering educators will leave the special session understanding the value of fundamental principle retention activities and take away several resources to implement these activities in their classes. They will have experienced them firsthand from the student perspective, so they will be able to adapt the activities to their students and learning environment.

Future work includes possible collaboration with participants to share and reflect upon their experiences and challenges of implementing these techniques with a broader variety of courses and students. We hope through this session that these strategies will be disseminated to a wider engineering education community.

References

[1] U. Boser, "Learn Better", Rodale, 2017.

[2] H. de Boer, A. Donker, and D. Kostons, "Effective Strategies for Self-Regulated Learning: A Meta-Analysis," Groningen: GION (Gronings Instituut voor Onderzoek van Onderwijs), Rijksuniversiteit Groningen, 2013.

[3] D. Christodoulou, "Seven Myths about Education," London: Taylor and Francis, 2013.

[4] W. Thalheimer, "How Much Do People Forget?," [Online]. Available: https://www.worklearning.com/wp-content/uploads/2010/12/How-much-do-people-forget-v12-14-2010.pdf. [Accessed June 5, 2018].

[5] P Smole, Y. Zhang, and J. Byrne, "The Right Time to Learn: Mechanisms and Optimization of Spaced Learning," Nature Reviews Neuroscience vol. 17, no. 2, Feb. 2016.

[6] J. Dunlosky, K. Rawson, E. Marsh, M. Nathan, and D. Willingham, "Improving Students' Learning with Effective Learning Techniques: Promising Directions from Cognitive and Educational Psychology," Psychological Science in the Public Interest, vol 14, no 1, pp, 4 - 58, Jan. 2013.

[7] D. Kolb, "Experiential Learning: Experience as the Source of Learning and Development", Prentice-Hall, Englewood Cliffs, NJ, 1984.

[8] J. Heywood, "Engineering Education Research and Development in Curriculum and Instruction", Wiley and Sons, 2005.

[9] B. Kort and R. Reilly, "A Pedagogical Model for Teaching Scientific Domain Knowledge," Proceedings of Frontiers in Education Conference, Boston, Massachusetts, Nov. 6-9, 2002.

[10] R. Culver and C. Yokomoto, "Optimum Academic Performance and its Relation to Emotional Intelligence," Proceedings in Frontiers in Education Conference, San Juan, Puerto Rico, Nov. 10-13, 1999.

[11] T. Byers and W. Imms, "Does the space make a difference? New Generation Learning Spaces Project", Churchie, 2018.

[12] R. Felder and L. Silverman, "Learning and Teaching Styles in Engineering Education," Engineering Education, vol. 78, no. 7, pp. 674 681, Apr. 1988.

[13] K. Kapp, "The Gamification of Learning and Instruction: game-based methods and strategies for training and education", Pfeiffer, 2012.

[14] Aalborg University, Denmark, "Problem based Project Work at Aalborg University," [Online]. Available: http://www.en.aau.dk/education/problem-based-learning/project-work/. [Accessed: Jan 30, 2018].

[15] R. Ulseth and B. Johnson, "Iron Range Engineering PBL Experience", in PAEE 2015 International Symposium on Project Approaches in Engineering Education, International Joint Conference on the Learner in Engineering Education, Donostia-San Sebastian, Spain, July 6-9 2015.

[16] "Plickers," [Online]. Available: https://plickers.com/. [Accessed: Jan 30, 2018].

[17] "Kahoot," [Online]. Available: https://kahoot.com/. [Accessed: Jan 30, 2018].