Cognitive Learning in Introductory College Science Education

<u>Eileen M. Kowalski</u>, Department of Chemistry and Life Science, and Joe D. Manous, Jr., Department of Geography and Environmental Engineering, United States Military Academy

Abstract

This research seeks to categorize dominant areas of cognitive learning weakness and strength within traditional college-level, introductory science education. The basis of any undergraduate STEM education is an understanding of fundamental concepts and how these concepts describe or predict physical phenomena. However, the apparent retention and understanding of basic concepts is sometimes minimal as expressed by student work during subsequent courses.

Potential causes for this difficulty in learning transfer are an inability to articulate concepts, weak association of concepts with theory, poor problem solving skills, or a limited understanding of specific disciplines such as mathematics, chemistry, physics, or biology.

We interviewed three cohorts (e.g., successive academic years) of college seniors majoring in environmental engineering to assess individual retention of basic skills in chemistry using the "Think Aloud Methodology".[15] At a minimum, each student had completed two courses in general chemistry, one course in environmental chemistry, and three courses in environmental engineering process design that employed chemistry. The interviews consisted of individual students working selected chemistry based problems on a blackboard, while they described their rationale and methodology to members of the Chemistry and Environmental Engineering faculty. Each student was provided the same selection of problems.

Outcomes of these interviews are presented as trends in recall of basic facts (e.g., students know that brackets indicate concentration in molarity), concept recognition (e.g., students identify conservation of energy in a heat transfer problem), or general problem solving skills (drawing sketches, identifying known and unknown variables). The strength or weakness in conceptual understanding will be compared to the students' exposure to these concepts in the college curriculum. The discussion also includes an analysis of fundamentals (e.g., mathematics) related to the Chemistry concepts under consideration.

Introduction

Traditional engineering education assumes key basic science and engineering science concepts can be studied and learned using lecture, recitation, problem sets, and design problem methods in an undergraduate program. In practice, this assumption may not be true or even practical. Compounding the issue is the identification of which concepts are key as educators and practioners have differences of opinion as to which concepts belong in this category. Also at issue is the adoption of academic outcome goals,[2] which generally include a goal that engineering education provides the undergraduate with the technical skills and requisite knowledge needed to be productive as they start their next field of endeavor, whether graduate studies or engineering practice. Clearly, this outcome goal is entirely desirable.

The challenge in developing realistic education outcome goals has become increasingly difficult as the body of knowledge required to be conversant, much less master, a field has grown at an increasing rate over the past century.[3] To illustrate, the fields of geotechnical engineering, electrical engineering, environmental engineering, and biological engineering, to name a few, were all created in the past 90 years. In addition to new fields of endeavor, the introduction of technology, especially the personal computer, has greatly expanded the opportunities for exploration, testing, and publishing in all fields of science, technology, engineering and math (STEM). These achievements are a great boon for humankind, but a tremendous challenge for educators as they prepare students to join, midstream, the rapid growth in STEM knowledge.

Attempts to make the educational experience more effective have generally followed two pathways, linking courses together to enhance the cumulative learning effect,[7,8] or increasing the effectiveness of individual student experiences. Linking courses together has the combined effect of repetition and providing an overarching problem in which the student can see how concepts from various courses interrelate. Increasing student learning effectiveness comprises a variety of techniques to include presentation style, use of demonstrations and technology, and the development of problems sets and design problems.[5,6,12,13,16] While these improvements in learning effectiveness are substantial benefits to the education process, they do not completely address how to place our accumulated engineering knowledge in a four-year program.

The "traditional" method of engineering education has served the public well. The outstanding question is whether these methods meet the needs of an expanding knowledge base in the 21st Century. The traditional method operates on the assumption that exposure to material with repetition through homeworks and designs is sufficient to provide the learning necessary for the next step in the education process. However, this assumption has not been rigorously challenged within engineering education. If this assumption is incorrect then the class hours spent in the study of basic science and basic engineering topics might not be the most productive use of these learning opportunities. While it can be argued that passing these types of STEM courses does demonstrate a capability to solve problems—an important evaluative and developmental step—the method may not best meet the needs of higher education in the future. Consequently, a useful area of investigation is determining the level of information retention provided by existing engineering education methods and the supporting linkages to cognitive learning.

Purpose

This research seeks to establish cause and effect relationships between traditional engineering education and cognitive learning to evaluate the success of traditional education methods in promoting cognitive learning.

Background

Cognitive learning is an area that has been studied in some detail by the education profession. In essence, it describes learning where a student understands and can recall a concept after an extended period. The ability to understand a concept is not exactly the same as long-term memory, but there is a correlation when discussing cognitive learning. While the human mind has extraordinary capabilities to reason and recall, it does not store whole thoughts, but rather reconstructs thoughts from individual clues. In addition, long term memory can be affected by decay of the physical trace in the brain through physical damage or aging, interference caused by inconsistencies with "known" information and new observations, or a lack of retrieval clues.[11] As some clues become deeply imbedded, they develop into building blocks for multiple memories. The ability of a human mind to reconstruct and understand ideas from individual clues long after an idea is "learned" constitutes cognitive learning. Unfortunately, much of the material studied in the classroom does not become deeply imbedded and falls into the category of short-term memory. The process of cognitive learning is complex, not well understood, and varies between individuals. However, there does seem to be a positive relationship between experiences requiring student engagement and enhancement of cognitive learning. These experiences do have a cost in that they require more time to accomplish than "traditional" lecture classes and consequently result in less material covered within an academic course. As the concept of cognitive learning is different from traditional lecture instruction, it may be difficult for many teachers to accept. Not only will the style of course differ, but if the premise of experience developing cognitive learning is correct, then fewer topics can be taught within a semester. If fewer topics can be effectively covered and the volume of available information increases, an interesting dilemma for faculty becomes apparent.

While the investigation of cognitive learning within the engineering profession is rather new, it has been accepted by other fields of education with the most notable being the study of medicine. Until recently, the four-year medical school experience centered around lecture and laboratory work, somewhat similar to engineering education, with clinical work occurring primarily during the fourth year. Today many medical schools include clinical experience early in the medical school experience because students have demonstrated a better grasp of material when they are concurrently studying in "traditional" courses and experience greater cognitive learning through the combination of clinical (problem-based learning) and lecture activities.[1] A similar inclusion of practicums in engineering education might yield equal benefits,[10] but care is required when comparing a four-year post baccalaureate medical school experience with an undergraduate engineering education. There are significant differences in the program outcomes and student populations. In any case, increasing the level of cognitive learning would seem a worthy goal in both programs. Consequently, a useful area for educational research is to determine the level or degree of cognitive learning resulting from existing traditional education experience and the identification of opportunities to increase this result.[9,14]

Method

To investigate cognitive learning, the authors conducted a three-year research program to assess a specific area of basic science education, general chemistry, within an environmental engineering education. Chemistry was selected as an area of investigation because of its repetitive application within the environmental engineering curriculum and, as such, provides a basic science topic that should be reasonably well understood by all environmental engineering undergraduates. Three successive cohorts of 12 seniors majoring in an ABET accredited environmental engineering program at the United States Military Academy were interviewed a few weeks before graduation on selected chemistry topics. Each student was presented with five questions (Table 1) and asked to work the problems on a blackboard, explaining to the interviewers their thought process as they proceeded. The sessions were one hour in length and videotaped.

Questions were ordered with the simplest and most familiar topics first to build student confidence during the interview. The first question about balancing an equation was designed as a "warm-up", to get students comfortable with working at the board and vocalizing their ideas. The second question on the pH of sulfuric acid was slightly more difficult and complex. However, as environmental engineering majors, the students had seen problems similar to this many times in several different classes. Successive questions addressed more complex and less familiar topics, so that students were increasingly challenged as the interview progressed.

The use of oral examinations was modeled after "The Think Aloud Method" by van Someren *et al*.[15] This qualitative assessment procedure was selected because it provides a clearer picture of cognitive learning than a review of written problem solutions. Since cognitive memory is reconstructed from various saved clues, the researchers are able to supplement and record clues when a student is unable to proceed. Consequently, the number and type of clues provided to a student yields an indication of the cognitive learning level for that particular topic.

Table 1 – Questions used to interview environmental engineering majors by the Think Aloud Method for qualitative assessment.

#	QUESTION	PURPOSE
1	Balance the following reaction: $SF_{6(g)} + SO_{3(g)} \leftrightarrow SO_2F_{2(g)}$	Chemical stoichiometry
2	If 100 mg of H_2SO_4 are added to 1 liter of water (pH = 7.0), what is the final pH of the solution?	Acidic character and basic math (i.e., logarithms)
3	A 28.2 g sample of an alloy is heated to 195 ºC and then added to 50.6 g of water at 25.3 ºC. The final temperature of the solution is 48.5 ºC and the specific heat capacity of the water is 4.184 J/gºC. Using a list of potential alloys and their specific heat capacities, set up a solution and explain how to identify the unknown alloy.	Energy balance and material properties
4	In a sealed vessel, the partial pressure of Trichloroethylene (TCE) measured in the air space above a liquid is 50 kPa. What is the concentration of TCE (mg/L) in solution?	Mass balance
5	Will C_2H_5OH (ethanol) and CH_3OCH_3 (dimethyl ether) be soluble in one another and which will have the highest boiling point? Explain the basis for your conclusions.	Molecular properties and intermolecular forces

Four potential areas of cognitive learning were investigated.

1. Rote recall of facts or equations.
2. Associating relevant concepts and theories with questions.
3. Conceptual understanding—using assumptions, facts, and boundary conditions; expressing ideas clearly and correctly.
4. Problem solving skills—identify appropriate steps, extrapolate science to new problems.[4]

Assessment

Working with West Point cadets provides a moderate level of similarity in educational backgrounds. Each cadet takes two semesters of general chemistry during their freshman year, except those that validate chemistry through high school advanced placement. All of the cadets take courses in Environmental Chemistry, Environmental Biology, Physical and Chemical Treatment Processes, Biological Treatment Processes, and Differential Equations at the same time in their academic experience and with the same teacher. All of the cadets also take three semesters of calculus and two semesters of physics while in residence at the Academy. This homogenous population facilitates comparisons between and within cohorts.

Actions or concepts related to each of the five questions posed to students were developed and then categorized according to the four areas of cognitive learning. Videotapes and notes from the interview were reviewed to determine how often students had demonstrated each action or concept. Results are tabulated in Table 2. Not all students were asked all questions due to time constraints, so the value of “n” varies within each cohort.

Table 2 – Observed behaviors of students during the interview, grouped by the four areas of cognitive learning listed. Data are reported as (number of students who demonstrated this behavior)/(number of students asked). Not all students were asked all questions due to time constraints.

Area of Learning	Question	Observations	Class of 2005	Class of 2006	Class of 2007	Totals
Rote recall	2	Recall pH equation	7/12	7/12	7/11	21/35
	2	Know units for [ ]	4 yes, 5 no	6 yes, 5 no	1 yes, 6 no	11 yes, 16 no
	3	Recall q = mc(delta T)	3/12	5/12	4/11	12/35
	4	Recall Henry's Law	4/10	3/12	1/11	8/33
	4	[ ] constant at equilibrium	1/10	3/11	1/11	5/32
	5	Describe polarity correctly	0/7	0/8	0/6	0/21
Relevant concepts	2	Dissociate H_2SO_4 correctly	9/12	7/12	4/11	20/35
	2	Write charges on ions	7/12	7/12	3/11	17/35
	3	Identify energy balance	5/12	6/12	4/11	15/35
	3	ID energy balance w/coaching	2/12	4/12	5/11	11/35
	4	Identify Henry's Law	6/10	9/12	3/11	18/33
	4	Suggest Ideal Gas Law	2/10	2/11	3/11	7/32
	4	Suggest Dalton's Law partial P	3/10	2/11	3/11	8/32
	5	Relate polarity and charge	4/7	6/7	2/6	12/20
	5	Relate polarity and shape	0/7	2/7	2/6	4/20
	5	Draw Lewis dot structure	4/7	2/7	3/6	9/20
Conceptual Understanding	1	Balance reaction correctly	11/12	11/12	11/11	33/35
	2	Write unbalanced reaction	3/12	4/12	3/11	10/35
	2	Articulate usefulness of mole	4/9	7/11	6/11	17/31
	3	Write heat lost = heat gained	8/12	9/12	4/11	21/35
	3	Omit temperature difference	3/11	4/12	4/11	11/34
	3	Add masses	2/11	2/12	3/11	7/34
	3	State assumptions	1/12	2/12	0/11	3/35
	4	Describe dynamic equilibrium	2/10	4/12	1/11	7/33
	4	Particles constantly moving	10/11	9/12	6/11	25/34
	4	1 phase change causes opposite	6/10	7/12	5/11	18/33
	5	Check sol. constant in water	3/7	3/7	3/6	9/20
Problem Solving Skills	1	Check solution at end	12/12	11/12	9/11	33/35
	2	Convert mg to moles	10/12	8/12	10/11	28/35
	2	Correctly use order of magnitude	10/11	9/11	8/11	27/33
	3	Draw picture on own initiative	3/12	4/12	1/11	8/35
	3	Draw picture after prompting	5/12	4/12	6/11	15/35
	3	Organize given	9/12	9/12	4/11	22/35
	3	Derive equation by units	9/12	7/12	4/11	20/35
	3	Derive solution in variables only	0/12	3/12	2/11	5/35
	4	Draw picture on own initiative	7/10	4/11	3/11	17/32
	4	Draw picture after prompting	1/10	4/11	7/11	12/32
	4	Identify empirical equation	3/10	8/11	6/11	17/32
	4	Identify limits of empirical eq	0/10	9/11	5/11	14/32
	4	Identify >1 ways to decrease P	9/10	11/12	7/11	27/33
	5	Octanol-water partition	1/7	2/7	0/6	3/20

Questions involving rote recall had a relatively low response rate among students. Students were not given the questions or topics beforehand, nor were they expected to study for the interview. Several students expressed a wish to find equations in the Fundamentals of Engineering Examination (FEE) handbook or a similar reference that would be available to them as a practicing engineer.

Students' success at identifying relevant concepts generally related to how often they had seen the material during their coursework. For example, identifying sulfuric acid (H_2SO_4) as a strong acid and properly dissociating it into ions (question 2; see Table 1) was a task students had done in three separate courses. Polarity and solubility (question 5) were less familiar concepts which the students had difficulty recalling and discussing.

An exception to this trend was the energy balance problem in question 3. Although students had dealt with conservation of energy problems in classes during all four years of college, many of them had trouble recognizing that energy balance was a key concept in this problem. The most common "wrong path" was to misidentify the question as a mass balance question. Some students who made this mistake commented that mass was more concrete and therefore easier to understand or work with than energy.

The conceptual understanding observations show some interesting contrasts. Only 2 of 35 students incorrectly balanced the chemical reaction in question 1, but 10 of the 35 wrote an unbalanced reaction for the dissociation of H_2SO_4 in their solution for question 2. This can be attributed to the additional complexity of question 2 compared to question 1. Balancing a reaction as an embedded task within a problem is more difficult than balancing a reaction as a stand-alone task.

The contrast between the students' knowledge that particles are constantly moving at equilibrium (25 out of 34) and their ability to describe dynamic equilibrium correctly (7 out of 33) is interesting. It indicates that the students have only partial understanding of the molecular level of processes.

Different students demonstrated different levels of problem solving skills. As a group, the students demonstrated great comfort with dimensional analysis. Again, the complexity of the task played a role. 28 out of 35 students could convert milligrams to moles in question 2, but only 20 out of 35 cadets could develop the equation they needed for question 3. One student stated that he tended not to use dimensional analysis. Instead, he input numbers into his calculator in various combinations until he got a reasonable answer. At the other extreme, five students could completely develop their equation for question 3 using variables. This indicates a high level of formative thinking by those students.

Advanced problem solvers frequently use sketches or diagrams to organize or understand the given information.[4] In question 3, only 8 of 35 students chose to draw a sketch of the problem. Seventeen more drew a sketch at the prompting of the interviewers. Two declined to draw a sketch at all. One student explained that sketches were not helpful to him, and the other stated that drawing sketches tended to work to his disadvantage. Question 4 shows a carryover effect, where 14 out of 32 students drew a sketch on their own initiative.

Additional analysis of the data is continuing. Examining the data by individual student instead of by year group should reveal patterns of weaknesses or strengths in cognitive learning. Correlating these patterns to other metrics of student ability such as grades, SAT scores, or FEE scores will also be done. Finally, student outcomes need to be correlated to how often and how thoroughly each concept is taught during the four-year curriculum.

Conclusions

Qualitatively assessing cognitive learning based on interviews does provide usable results. We were able to identify trends among and within three successive year groups of students soon to graduate with degrees in Environmental Engineering. Further information could be obtained by analyzing each student's performance separately to correlate weaknesses or strengths in cognitive learning.

In addition, the interactive nature of the oral interview enables interviewers to probe the limits of a student's learning and better assess the nature of a shortcoming when one is detected. In effect, the oral examination provides an input mechanism to supply clues that supplement incomplete cognitive learning and thereby assist students in remembering a concept. This ability to supplement existing cognitive learning allows researchers to probe beyond the limits of a written response to a question. The interactive exchange between interviewer and student also helped identify and define the input variables to the cognitive learning process. Again, the synthesis of the one-hour interviews facilitated the assessment of input variables in a way not replicable through written examination or survey.

Bibliography

1. Anderson, William L. and Robert H. Glew (2002) "Support of a Problem-Based Learning Curriculum by Basic Science Faculty". *Medical Education Online*. 7:10. Available from URL http://www.med-ed-online.org
2. ASCE (2003) "Civil Engineering Body of Knowledge for the 21st Century: Preparing the Civil Engineer for the Future, Draft 6". Body of Knowledge Committee. American Society of Civil Engineers. Reston, VA
3. Bergendahl, J.A. (2005) "Toward a Broader Technical Education for Engineers". *Journal of Professional Issues in Engineering Education and Practice*. 131:4, 257-262.
4. Camacho, M., and Good, R. (1989) "Problem Solving and Chemical Equilibrium: Successful versus Unsuccessful Performance". *Journal of Research in Science Teaching.* 26:3, 251-272.
5. Estes, Allen C., Ronald W. Welch, and Stephen J. Ressler (2004) "Questioning: Bring Your Students Along on the Journey". *Journal of Professional Issues in Engineering Education and Practice*. 130:4, 237-242.
6. Estes, Allen C., Ronald W. Welch, and Stephen J. Ressler (2005) "Teaching Lessons Learned: The ExCEEd Teaching Model". *Journal of Professional Issues in Engineering Education and Practice*. 131:4, 218-222.
7. Friesen, Marcia, K. Lynn Taylor, and M.G. Britton (2005) "A Qualitative Study of a Course Trilogy in Biosystems Engineering Design". *Journal of Engineering Education*. 94:3, 287-296.
8. Grigg, Neil S., Marvin E. Criswell, Darrell G. Fontane, Laurel Saito, Thomas J. Siller, and Daniel K. Sunada (2004) "Integrated Civil Engineering Curriculum: Five-Year Review". *Journal of Professional Issues in Engineering Education and Practice*. 130:3, 160-165.
9. Light, Richard J., Judith D. Singer, and John B. Willett (1990) By Design, Planning Research on Higher Education. Harvard University Press, Cambridge, 296p.
10. Newstetter, Wendy C. (2005) "Designing Cognitive Apprenticeships for Biomedical Engineering". *Journal of Engineering Education*. 94:2, 207-213.
11. Reese, Andy C. (1998) "Implications of Results From Cognitive Science". *Medical Education Online*. 3:1. Available from URL http://www.med-ed-online.org.
12. Ressler Stephen J. (2004) "Whither the Chalkboard? Case for a Low-Tech Tool in a High-Tech World". *Journal of Professional Issues in Engineering Education and Practice*. 130:2, 71-73.

13. Ressler Stephen J., Ronald W. Welch, and Karl F. Meyer (2004) "Teaching Lessons Learned: Organizing and Delivering Classroom Instruction". *Journal of Professional Issues in Engineering Education and Practice*. 130:3, 153-156.

14. Van de Ven (2000) "Professional Science for a Professional School: Action Science and Normal Science" Breaking the Code of Change, chapter 19, edited by Michael Beer and Nitin Nohria. Harvard Business School Press. Boston, 512p.

15. van Someren, Maarten W., Yvonne F. Barnard, and Jacobijn A.C. Sandberg (1994) The Think Aloud Method: A Practical Guide to Modelling Cognitive Processes. Academic Press, London, 218p.

16. Welch, Ronald W., Stephen J. Ressler, and Allen C. Estes (2005) "A Model for Instructional Design". *Journal of Professional Issues in Engineering Education and Practice*. 131:3, 167-171.