AC 2007-88: LEARNING TO SOLVE PROBLEMS BY SCAFFOLDING ANALOGICAL ENCODING

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Learning to Solve Problems by Scaffolding Analogical Encoding

In order to teach students how to solve problems in most science and engineering courses, instructors demonstrate how to solve a problem and then ask learners to apply that method to a new transfer problem. Transferring learning from a single example to a new problem requires that learners induce a schema for that kind of problem from that single example and then apply that schema to a new, contextually varied problem. This single-example approach to teaching problem solving usually results in students attempting to mimic the process for solving the problem while ignoring the semantic, structural characteristics of the problem. As a result, when asked to compare problems or transfer solution methods to more contextually varied problems, student typically generalize problem solutions based on surface level similarities among problems (Chi et al, 1981; Dufresne, Gerace, Hardiman, & Mestre, 1992; Hardiman, Dufresne, & Mestre, 1989; Schoenfeld & Herrmann, 1982). When asked to recall problems, students recall relevant examples, especially when the two problems differ in surface features, because people focus on surface features (Gentner, 1989; Medin & Ross, 1989). Loewenstein, Thompson, and Gentner (1999) showed minimal transfer from a single example. Unfortunately, transfer from a single problem is insufficient for schema induction.

In order to transfer problem solutions, students must induce a conceptual model (schema) for the kind of problem being solved. The most successful methods for teaching problem solving support student construction of problem schemas (Taconis, Fergusson-Hessler, & Broekkamp, 2001), because it is the quality of students' conceptual model that most influences the ease and accuracy with which problems can be solved (Hayes & Simon, 1976). To solve problems consistently, learners must demonstrate conceptual understanding of the problems by constructing problem schemas for each kind of problem (e.g., conservation of momentum, angular motion, or kinematics in physics) that includes semantic and situational information about the problem that is associated with the procedures for solving that type of problem (Reusser, 1993).

Problem-solving transfer is based on schema induction and reuse, which is a form of analogical reasoning. Extensive research by Gentner and her colleagues has shown that comprehension and schema induction is greatly enhanced by analogical encoding, where learners compare two analogues for their structural alignment. Analogical encoding is the process of mapping structural properties between multiple analogues. Rather than attempting to induce and transfer a schema based on a single example, Gentner and her colleagues have shown that comprehension, schema induction, and long term transfer across contexts can be greatly facilitated by comparing two analogues for structural alignment (Catrambone & Holyoak, 1989; Gentner, & Markman, 1997; Gentner, & Markman, 2005; Loewenstein, Thompson, & Gentner, 1999; Loewenstein, Thompson, & Gentner, 2003). When learners directly compare two examples, they can focus on structural similarities, but if presented with just one example, they are far more likely to recall examples based on surface features. Analogical encoding fosters learning because analogies promote attention to structural commonalities, including common principles and schemas (Gick & Holyoak, 1983).

As a methodology, analogical encoding has been applied primarily to domain-neutral problems, such as Duncker's X-ray problem. Some research (Gentner, Lowenstein, & Thompson, 2003; Loewenstein, Thompson, & Gentner, 2003) has confirmed the effects of analogical encoding in learning negotiation strategies. None of the analogical encoding research has ever been applied to complex, multi-faceted science and engineering problems. Second, the most important factor in analogical encoding is the depth of the comparison process.

Analogical encoding research has been very successful in part because mapping structural elements between simpler problems requires fewer cognitive resources. With more complex STEM problems, structural alignment will likely require more than directions to compare problems, especially given the tendency among students to compare them based on surface features of the problem. Spencer and Weisberg (1996) showed that presentation of multiple source analogs is not sufficient to ensure transfer across contexts. Instruction to support analogical encoding is necessary. Merely reading or receiving multiple cases is not enough to produce comparison effects (Loewenstein et al, 1999). In order to support that comparison process, intensive structural comparisons must be made.

Supported by a NSF CCLI grant, we are examining how two different treatments can be used to support analogical encoding among engineering and physics problems in order to facilitate structural alignment. Our research will compare structural alignment questions with a graphical structure mapping strategy. The purpose of both treatments is to focus student's attention on the alignment between structurally similar problem pairs.

Our research supports analogical encoding between problems by providing questions relevant to each problem pair, similar to the system described by Graesser, Langston, and Lang (1992). Catrambone and Holyoak (1989) provided schema oriented questions to help learners focus on problem-relevant aspects of the story. They found that presentation of extensive comparison questions along with three analogs sufficient to enable transfer to superficially dissimilar target in the absence of hints.

In the structure mapping treatment, students will identify on a structural map of different kinds of problems the elements and relationships in each problem in a side-by-side comparison.

Physics Problems

During the spring, 2007 semester, we are conducting research in introductory physics classes at Kansas State University and the University of Missouri.

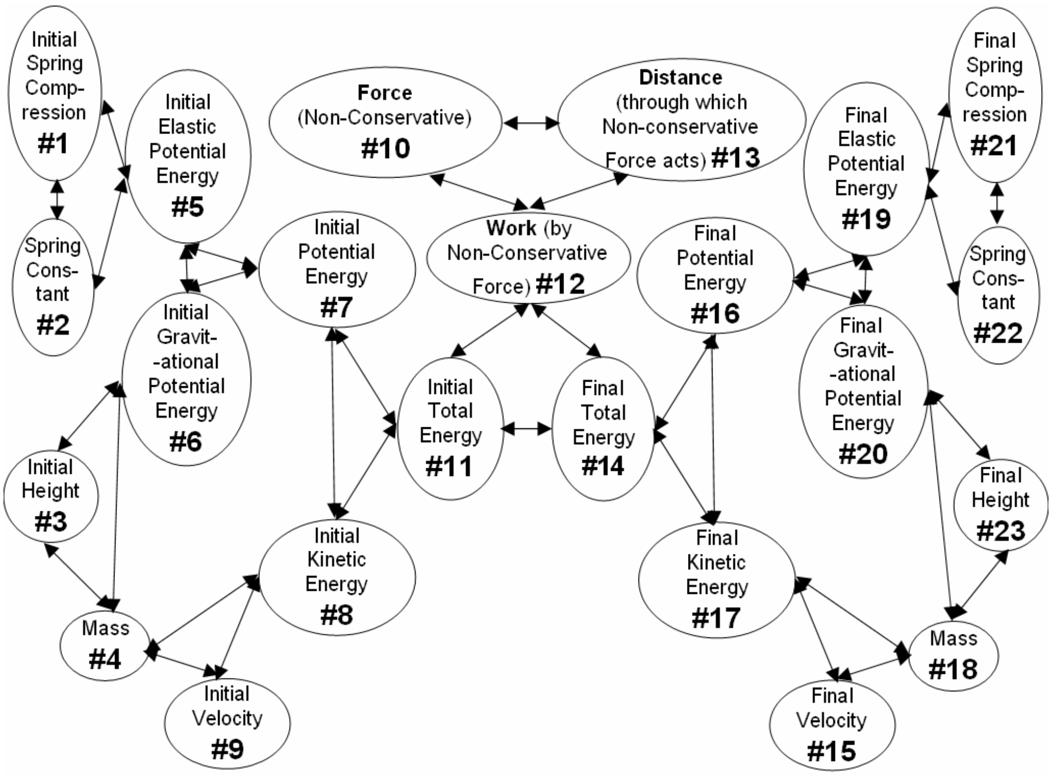
At Kansas State University, we are collecting data in an advanced introductory course, Descriptive Physics, intended for architecture majors. We have developed a web-based environment that presents pairs of problems and then asks questions about those problems one at a time (see Figure 1 for sample questions related to work-energy).

Problem 1 (Giancoli 6-19) A 0.088kg arrow is fired from a bow whose string exerts an average force of 110N over a distance of 0.78m. Neglecting air resistance, what is the speed of the arrow as it leaves the bow?	Problem 2 (Giancoli 6-23) A 0.25kg softball is pitched at 26m/s. By the time it reaches the plate a distance 15m away it has slowed to 23m/s. Neglecting gravity, what is the average force of air resistance during the pitch?
Q1-1 Which of the following quantities are directly given in the Problem 1? Select all that apply. a.) Initial speed of the arrow b.) Final speed of the arrow c.) Mass of the arrow d.) Forces on the arrow e.) Distance traveled by the arrow. f.) None of the above. Optional comment regarding your answer:________________________ ANSWER: a, c, d, e	Q2-1 Which of the following quantities are directly given in the Problem 2? Select all that apply. a.) Initial speed of the softball. b.) Final speed of the softball. c.) Mass of the softball. d.) Forces on the softball. e.) Distance traveled by the softball. f.) None of the above. Optional comment regarding your answer:________________________ ANSWER: a,b,c,d,e
Q1-2 In general, Problem 1 could be solved by applying. Select all that apply. a.) Newton's Second Law of Motion b.) Work - Energy Theorem c.) Conservation of Mechanical Energy d.) Conservation of Linear Momentum. e.) None of the above. Optional comment regarding your answer:________________________ ANSWER: a,b	Q2-2 In general, Problem 2 could be solved by applying. Select all that apply. a.) Newton's Second Law of Motion b.) Work - Energy Theorem c.) Conservation of Mechanical Energy d.) Conservation of Linear Momentum. e.) None of the above. Optional comment regarding your answer:________________________ ANSWER: b
Q1-3 Which of the following physical quantities change in Problem 1? Select all that apply. a) Kinetic Energy of the arrow. b) Elastic Potential Energy of the arrow. c) Gravitational Potential Energy of the arrow. Optional comment regarding your answer:________________________ ANSWER: a	Q2-3 Which of the following physical quantities change in Problem 2? Select all that apply. a) Kinetic Energy of the softball. b) Elastic Potential Energy of the softball. c) Gravitational Potential Energy of the softball. Optional comment regarding your answer:________________________ ANSWER: a
Q1-4 Identify the non-conservative forces acting on the arrow in Problem 1. Select all that apply. a.) Force of the bow b.) Force of gravity c.) Force of air resistance d.) There are no non-conservative forces acting on arrow. Optional comment regarding your answer:________________________ ANSWER: a (isn't it still conserved)	Q2-4 Identify the non-conservative forces acting on the softball in Problem 2. Select all that apply. a.) Force of the plate. b.) Force of gravity. c.) Force of air resistance. d.) There are no non-conservative forces acting on softball. Optional comment regarding your answer:________________________ ANSWER: c

Figure 1. Structural alignment questions for work-energy problems.

Similar questions are being used in an introductory, algebra-based physics course at the University of Missouri. The questions are included in the class WebCT website as part of their regular homework We have collected data using similar questions for kinematics problems and will be collecting data on work-energy problems during March, 2007.

For the structure mapping treatment, we constructed a map showing functional relationships among all of the possible elements in work-energy problems. In the web-based environment, students are shown the map along with the problem pairs and reqired to compare the values in embedded in the problem to the map (see Figure 2).



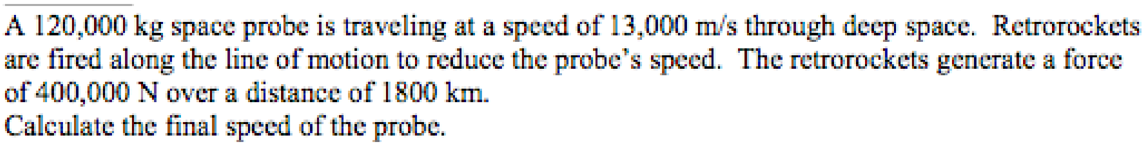
Problem 1	Problem 2
A 0.088kg arrow is fired from a bow whose string exerts an average force of 110N over a distance of 0.78m. Neglecting air resistance, what is the speed of the arrow as it leaves the bow?	A 0.25kg softball is pitched at 26m/s. By the time it reaches the plate a distance 15m away it has slowed to 23m/s. Neglecting gravity, what is the average force of air resistance during the pitch?
Q1-1 What part(s) of the structure map is/are best representative of "A 0.088 kg arrow is fired from a bow"?	Q2-1 What part(s) of the structure map is/are best representative of "A 0.25 kg softball is pitched"?
Q1-2 What part(s) of the structure map is/are best representative of "string exerts an average force of 110 N"?	Q2-2 What part(s) of the structure map is/are best representative of "pitched at 26 m/s"?
Q1-3 What part(s) of the structure map is/are best representative of "over a distance of 0.78 m."?	Q2-3 What part(s) of the structure map is/are best representative of "By the time is reaches the plate a distance 15m away"?

Figure 2. Structure map of work-energy problems in physics.

At the University, similar treatments will be used in junior level circuits course offered by the electrical engineering department. In this course, students study electronic materials in equilibrium and band theory in solids for determining the net flow of electrons and holes for the generation of current. This includes the study of two basic transport mechanisms due to electric fields and density gradients in electronic devices. These problems serve as the foundation for determining current-voltage characteristics of semiconductor devices that are found in nearly all electronic platforms.

Problem Solving Assessment

Assessment of students problem solving includes traditional problem solution methods. During a normally scheduled examination, students solve structurally equivalent problems quantitatively (see Figure 3). In order to assess the quality of the problem schemas that students construct as an indicator of conceptual understanding, we will present three different kinds of conceptual questions on the examination as well. Second, students will answer text editing questions that present word problems to students. Rather than solving the problems, students are required to determine if there is sufficient information to solve problem, there is sufficient information plus irrelevant information to solve problem, or whether there is information required to solve problem is missing. This problem type is quite difficult for students. If students successfully answer the text editing questions, we will conclude that they have constructed better problem schemas. Third, students will be presented with pairs of problems and asked to rate the level of similarity of problems. If students judge problem similarity based on the structural similarity of the problems, we will conclude that they have constructed better problem schemas.



A 120,000 kg space probe is traveling at a speed of 13,000 m/s through deep space. Retrorockets are fired along the line of motion to reduce the probe's speed. The retrorockets generate a force of 400,000 N over a distance of 1800 km.
Calculate the final speed of the probe.

Figure 3. Structurally equivalent transfer problem.

Data are currently being collected in these different contexts. Preliminary analyses of the data will be presented at the 2007 ASEE meeting.

References

Catrambone, R.., Holyoak, K. J. (1989). Overcoming contextual limitations on problem-solving transfer. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15* (6), 1147-1156.

Chi, M.T.H., Feltovich, .J., & Glaser, R. (1983). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121-152.

Dufresne, R.J., Gerace, W.J., Hardiman, P.T., & Mestre, J.P. (1992). Constraining novices to perform expertlike problem analysis: Effects on schema acquisition. *Journal of the Learning Sciences, 2* (3), 307-331.

Gentner, D., Lowenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology, 95* (2), 393-405.

Gentner, D., & Markman, A.B. (1997). Structure mapping in analogy and similarity. *American Psychologist, 52* (1), 45-56.

Gentner, D., & Markman, A.B. (2005). Defining structural similarity. *Journal of Cognitive Science, 6*, 1-20.

Gick, M.L., & Holyoak, K.J. (1983). Schema induction and analogical transfer. *Cognitive Psychology 15*(1), 1-38

Graesser, A.C., Langston, M.C., & Lang, K.L. (1992). Designing educational software around questioning. *Journal of Artificial Intelligence in Education, 3*, 235-241.

Hardiman, P.T., Dufresne, R., & Mester, J.P. (1989). The relation between problem categorization and problem solving among experts and novices. *Memory & Cognition, 17*(5), 627-638.

Loewenstein, J., Thompson, L., Gentner, D. (1999). Analogical encoding facilitates knowledge transfer in negotiation. *Psychonomic Bulletin & Review, 6* (4), 58-597.

Loewenstein, J., Thompson, L., & Gentner, D. (2003). Analogical learning in negotiation teams: Comparing cases promotes learning and transfer. *Academy of Management Learning and Education, 2* (2), 119-127.

Reusser, K. (1993). Tutoring systems and pedagogical theory: representational tools for understanding, planning, and reflection in problem solving. In: Lajoie, S. P., and Derry, S. J. (eds.), *Computers as Cognitive Tools*, Lawrence Erlbaum, Hillsdale, NJ, pp. 143–178.

Schoenfeld, A.H., & Herrmann, D.J. (1982). Problem perception and knowledge structure in expert and novice mathematical problem solvers. *Journal of Experimental Psychology: Learning, memory, & Cognition, 8*, 484-494.

Spencer RM & Weisberg RW (1996). Context-dependent effects on analogical transfer. *Memory & Cognition, 14*, 442-449.

Taconis, R., Fergusson-Hesler, M.G.M., & Broekkamp, H. (2001). Teaching science problem solving: An overview of experimental work. *Journal or Research in Science Teaching, 38* (4), 442.468.