SCIENCE EDUCATION

Teaching Creative Science Thinking

Students' creative insights can be nurtured by promoting peer-peer learning and increasing associative thinking.

Robert L. DeHaan

Scientists frequently encounter ill-structured problems that can have multiple paths to multiple solutions (*1*). To approach such problems, "higher-order" mental operations such as analysis, synthesis, and abstraction are key. But, in addition, creative thinking—the most complex and abstract of the higher-order cognitive skills according to Bloom's taxonomy of learning skills (*2*)—can allow restructuring of problems and produce solutions through unexpected insights (*3*). Creativity is the root of the innovative thinking that leads to solutions or products that are novel, useful (*4*), and critical to economic success (*5*, *6*). I discuss below how students might be taught to think more creatively in the context of science, and how instructors can focus more on students' creative thinking, in addition to scientific reasoning and subject-matter content (*7*).

It is unfortunate that, in the classroom, we often teach as if creativity is not important, as if science deals only with well-structured problems with known answers and a single way to find the "correct" solution (*8*). Not only is no attention paid to creativity but also—with some exceptions (*9*, *10*)—there is little teaching of any of the higher-order cognitive skills. In a U.S. national sample of 77 undergraduate life science courses taught by 50 different instructors, fewer than 1% of the items on tests and quizzes required students to use any of these higher-level skills (*11*). Little wonder that only about one-fourth of U.S. college students have the reasoning skills necessary to solve conceptual problems (*12*).

An extensive literature is replete with instructional strategies to help students be more creative (*13*). Creativity is a complex, multicomponent construct and, therefore, is not easy to define or assess, especially in the context of science (*13*, *14*). Nonetheless, there is evidence that the cognitive operations that are required for creativity can be taught and that the instructional strategies that work best are relatively simple modifications of the active learning instruction that is most effective for teaching abstraction and problem-solving (*15*).

Division of Educational Studies, Emory University, Atlanta, GA 30322, USA. E-mail: rdehaan@emory.edu

Frameworks for Creativity

Creativity has been defined within two different theoretical frameworks. In one, a novel idea or solution to a problem occurs in the mind of an individual as a creative insight or an "aha" experience (*3*, *13*). In the other, creativity is a social phenomenon that relies on interaction among knowledgeable individuals (*14*). To produce a creative insight in an individual mind, two broad categories of mental operations are said to be required (*3*, *4*): associative (divergent) thinking, in which thoughts are defocused, intuitive, and receptive to a broad range of associations to a given stimulus, and analytical (convergent) thinking, the capacity to analyze, synthesize, and focus. One of numerous examples of a creative insight in science was reported recently by Francois Jacob on the discovery of the operon (*16*).

Neuroscience experiments show that associative thinking is cognitively quite different from analytical problem-solving. Brain regions such as the right superior temporal gyrus are activated to a greater degree in subjects solving remote association problems by insight (e.g., find a word that forms a compound word or phrase with each of the following three words: tooth, potato, heart; solution: sweet) in a functional magnetic resonance imaging scanner than in subjects solving problems by analytical reasoning (*17*). Associative thinking increases the probability of accessing weakly associated ideas (*18*).

A creative insight, then, is a sudden, unexpected recognition of concepts or facts in a new relation not previously seen (*19*, *20*). Such creative insights often follow conceptual reorganization or a new, non-obvious restructuring of a problem situation (*3*, *21*). The mechanism whereby two ideas are blended (*22*) or convoluted (*20*) by insight-like mechanisms into a third novel idea by a process termed "conceptual integration" (*23*) is an area of active research.

In contrast to the process of associative thinking in an individual brain, ethnographic analyses of interactions of scientists during lab meetings in highly productive laboratories show that new hypotheses or models are most often generated through discussions among knowledgeable peers (*14*, *24*). Faced with a series of unexpected results, a group of collaborating scientists suggest alternative hypotheses or models to test during lab discussions through a process termed "distributed reasoning" (*24*). This is most effective when the lab has scientists from diverse backgrounds who have worked with a range of different organisms and techniques. How formation of novel ideas through associative thinking in an individual is related to the production of new experimental designs or hypotheses through social interactions among a group of scientists is, again, an area for future research.

Cognitive studies of architects and industrial designers have shown that, to increase the creativity of their design solutions, experts in these fields use strategies to increase peer-peer interactions (as with brainstorming) and to prolong associative thinking. Faced with a design problem, they decompose and rearrange components in different contexts, striving to increase the range of associations they apply (*25*).

Associative thinking has been used as a proxy to test for creativity (*15*), and there are

Rubric* for responses to the challenge: "List as many uses as you can for a plastic bottle"

Criteria	3 points	2 points	1 point	0 points
Fluency	20 or more relevant responses	10–19 relevant responses	1–9 relevant responses	No relevant responses
Flexibility	14 or more different categories	6–13 different categories	2–5 different categories	All responses in the same category.
Originality	At least one response that is unique or common to no more than 10% of the population.	One or more responses that are novel; common to no more than 19% of the population.	One or more responses that are slightly novel; common to 20–49% of the population.	Responses common to 50% of fhe population; no novel responses.

* This rubric is expanded from the originality scoring checklist in (*13*).

well-established validated tests that can be adapted to the science classroom (*26*, *27*). I argue that science students, no less than design students, need assistance in enhancing peer-peer learning interactions and prolonging associative thinking when dealing with ill-structured problems.

Scientific Teaching

Scientific teaching refers to a group of instructional approaches intended to bring students into an active rather than passive learning mode (*28–30*)—strategies such as self-testing from memory (*31*) and peer-peer instruction, designed to promote active, engaged learning on the part of the student rather than rote memorization (*29*). But even in newer courses where active learning instruction with peer-peer interactions is employed, the emphasis has been limited to analysis, synthesis, and critical reasoning, the higher-order cognitive skills that are less abstract than creative thinking on Bloom's scale (*2*). We expect science students to solve problems, but we rarely refer to the creative aspects of the scientific discoveries that we teach (*32*). We do not routinely ask students to discuss problems together with peers (*33*) or to search for novel problem solutions through the extended exercise of associative thought. Students need to be reminded that there may be other ways to view a problem than the way it is presented; to list the problem features and then try to rearrange or restructure them or look at them from different angles (*3*); and to generate many ideas about possible solutions before beginning to evaluate which of them may be best (*3*, *8*).

A meta-analysis of 70 creativity training studies revealed that the number and diversity of associations could be increased by teaching students specific techniques to increase associative thinking (*15*). An example of a test to measure scientific creativity for high school students (*26*) has questions related to the "unusual uses" test found in the Torrance Test of Creative Thinking (*27*) (example: "If you can take a spaceship to travel… to another planet, what scientific questions do you want to research? List as many as you can."). These questions are scored in terms of the three accepted indicators of associative thinking (*13*, *15*): fluency (number of relevant responses), cognitive flexibility (number of different categories of responses), and originality (degree of novelty within a given population). A scoring rubric (*34*) defines levels of proficiency in these indicators within the population being tested (see the figure). This test, or a modified version, can be used to determine the effectiveness of efforts to teach students how to think more creatively, providing the feedback needed to drive further instructional innovations.

Below are some specific strategies that are thought to increase students' access to creative insights by promoting peer-peer learning and increasing associative thinking. With practice, each strategy should take no more than 4 min when inserted into a standard 50-min lecture (*35*).

Think-pair-share-create. This variation (*36*) of the classic think-pair-share strategy (*37*) is especially useful for fostering peer-peer reasoning and associative thinking in ill-structured problem-solving. Part-way into a lecture, the instructor poses an open-ended question or problem; gives students 1 min to think individually about an answer; asks them to pair with a neighbor to briefly discuss and reconcile their responses; reminds students to list the features of the problem, try to restructure or reframe their ideas, and think of as many solutions as they can; and finally, calls on several individuals or pairs (not volunteers) to share responses.

Peer instruction. The instructor poses a question and asks students first to find as many answers as possible on their own, again by feature-listing and reframing. They then attempt to justify their best answer to one or more of their peers, and finally they record a consensus response (*33*).

Think-aloud-pair–problem-solving. Retrieving information from memory (self-testing) is a better learning strategy for students than restudying the same information (*31*). In this maneuver (*35*), modified to promote associative thinking, the instructor poses a problem from previous readings for the class and has students form pairs, with one member serving as the "explainer" and the other as the "questioner." The explainers are given 2 min to recombine from memory components of the original problem into a new configuration with a different solution, and the questioner asks for clarifications or gives hints when necessary. This is repeated with a different problem at another point in the lecture, with the students in reversed roles. After the allotted time, the instructor calls on several explainers to report new solutions.

New research is needed on the roles associative thinking and distributed reasoning play in science and in creativity, as well as to test the hypothesis that teaching students to increase their associative thinking and their peer-peer interactions while problem-solving will improve the originality and novelty of the solutions they pose to ill-structured problems in science. A small but growing number of science instructors are already engaged in active learning pedagogies aimed at improving students' scientific reasoning skills (*10*). For them and their more reluctant colleagues, some of the strategies described above may be worth trying. If more students learn to think like creative scientists, it will be well worth the effort.

References and Notes

1. D. H. Jonassen, *Learning to Solve Problems: A Handbook for Designing Problem-Solving Learning Environments* (Routledge, New York, 2011).
2. D. R. Krathwohl, *Theory Pract.* **41**, 212 (2002).
3. E. M. Bowden *et al.*, *Trends Cogn. Sci.* **9**, 322 (2005).
4. M. A. Runco, *Annu. Rev. Psychol.* **55**, 657 (2004).
5. National Science Board, Preparing the Next Generation of STEM Innovators: Identifying and Developing Our Nation's Human Capital (2010); www.nsf.gov/nsb/publications/2010/nsb1033.pdf.
6. M. P. Feldman, in *Education for Innovation: Implications for India, China and America*, R. L. DeHaan, K. M. V. Narayan, Eds. (Sense Publishers, Rotterdam, 2008), pp. 49–62.
7. W. A. Anderson *et al.*, *Science* **331**, 152 (2011).
8. E. McWilliam, P. Poronnik, P. G. Taylor, *J. Sci. Educ. Technol.* **17**, 226 (2008).
9. P. C. Abrami *et al.*, *Rev. Educ. Res.* **78**, 1102 (2008).
10. M. A. Ruiz-Primo, D. Briggs, H. Iverson, R. Talbot, L. A. Shepard, *Science* **331**, 1269 (2011).
11. J. L. Momsen, T. M. Long, S. A. Wyse, D. Ebert-May, *CBE Life Sci. Educ.* **9**, 435 (2010).
12. M. S. Cracolice, J. C. Deming, B. Ehlert, *J. Chem. Educ.* **85**, 873 (2008).
13. R. L. DeHaan, *CBE Life Sci. Educ.* **8**, 172 (2009).
14. K. Dunbar, in *Mechanisms of Insight*, R. J. Sternberg, J. Davidson, Eds. (MIT Press, Cambridge, MA, 1995), pp. 365-395.
15. G. Scott, L. E. Leritz, M. D. Mumford, *Creat. Res. J.* **16**, 361 (2004).
16. F. Jacob, *Science* **332**, 767 (2011).
17. K. Subramaniam, J. Kounios, T. B. Parrish, M. Jung-Beeman, *J. Cogn. Neurosci.* **21**, 415 (2009).
18. P. L. Ansburg, K. Hill, *Pers. Individ. Dif.* **34**, 1141 (2003).
19. A. Koestler, *The Act of Creation* (Macmillan, New York, 1964).
20. P. Thagard, T. C. Stewart, *Cogn. Sci.* **35**, 1 (2011).
21. J. Kounios, M. Beeman, *Curr. Dir. Psychol. Sci.* **18**, 210 (2009).
22. F. C. Pereira, A. Cardoso, Conceptual Blending and the Quest for the Holy Creative Process; www.lsi.us.es/iberamia2002/confman/SUBMISSIONS/86-rapereicoc.pdf.
23. G. Fauconnier, M. Turner, *Cogn. Sci.* **22**, 133 (1998).
24. K. Dunbar, *Model-Based Reasoning in Scientific Discovery*, in L. Magnani, N. Nersessian, P. Thagard, Eds. (Plenum, New York, 1999), pp. 89–98.
25. M. H. Kim, Y. S. Kim, H. S. Lee, J. A. Park, *Des. Stud.* **28**, 585 (2007).
26. W. Hu, P. Adey, *Int. J. Sci. Educ.* **24**, 389 (2002).
27. K. H. Kim, *Creat. Res. J.* **18**, 3 (2006).
28. R. L. DeHaan, *J. Sci. Educ. Technol.* **14**, 253 (2005).
29. J. Handelsman, S. Miller, C. Pfund, *Scientific Teaching* (Freeman, New York, 2007).
30. W. B. Wood, *Annu. Rev. Cell Dev. Biol.* **25**, 93 (2009).
31. J. D. Karpicke, J. R. Blunt, *Science* **331**, 772 (2011).
32. D. K. Simonton, *Creativity in Science: Chance, Logic, Genius and Zeitgeist* (Cambridge Univ. Press, Cambridge, UK, 2004).
33. R. N. Cortright *et al.*, *Adv. Physiol. Educ.* **29**, 107 (2005).
34. D. Allen, K. Tanner, *CBE Life Sci. Educ.* **5**, 197 (2006).
35. R. M. Felder, R. Brent, *ASQ Higher Educ. Brief* **2**, 1 (2009).
36. D. W. Johnson, R. T. Johnson, K. A. Smith, *Active Learning: Cooperation in the College Classroom* (Interaction Book Co., Edina, MN, 1991).
37. F. Lyman, in *Mainstreaming Digest*, A. S. Anderson, Ed. (University of Maryland College of Education, College Park, MD, 1981).

38. The author thanks reviewers for constructive comments and M. Scharbo-DeHaan for careful reading and comments on revisions.

10.1126/science.1207918

Teaching Creative Science Thinking
Robert L. DeHaan (December 15, 2011)
Science **334** (6062), 1499-1500. [doi: 10.1126/science.1207918]

Editor's Summary