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Perspectives

Understanding Undergraduates' Problem-Solving Processes †

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Fostering effective problem-solving skills is one of the most longstanding and widely agreed upon goals of biology education. Nevertheless, undergraduate biology educators have yet to leverage many major findings about problem-solving processes from the educational and cognitive science research literatures. This article highlights key facets of problem-solving processes and introduces methodologies that may be used to reveal how undergraduate students perceive and represent biological problems. Overall, successful problem-solving entails a keen sensitivity to problem contexts, disciplined internal representation or modeling of the problem, and the principled management and deployment of cognitive resources. Context recognition tasks, problem representation practice, and cognitive resource management receive remarkably little emphasis in the biology curriculum, despite their central roles in problem-solving success.

INTRODUCTION

While problem-solving skills are universally recognized as a central goal of biology coursework (11) and formidable biological problems confront humanity as never before (10), one would be hard pressed to find biology educators (from any level of the educational hierarchy) who did not lament their students' deficiencies in this area. Why is this so? I argue that this dilemma should not be surprising given that remarkably few faculty have familiarized themselves with the cognitive processes involved in problem solving (7,15), the ways in which students internally *represent* the biological problems that we ask them to solve, and the cognitive resources *students* view as relevant to solving problems (4). Consequently, biology educators are too often ill-equipped to foster the development of the skills and dispositions that they so highly value. Paradoxically, knowing how to solve biological problems — as biologists clearly do — is *not* equivalent to knowing how to metacognitively conceptualize the *process* of problem solving, or to teach others this crucial skill. Yet this is the crux of the task for undergraduate biology faculty.

In an attempt to improve the teaching of problem solving in undergraduate biology (16), I briefly highlight some of the most salient aspects of problem-solving research central to this endeavor. My hope is that faculty will begin to re-envision the challenge of teaching problem solving in the life sciences. It is important to emphasize that — unlike in physics and chemistry education (8, 9) — problem-solving research in biology is remarkably incomplete and much remains to be known (23). I hope this article will catalyze interest, exploration, contemplation and further research in this crucial but neglected area of biology education.

Regardless whether biological problems are well-structured or ill-structured (16), in educational settings they are very often represented as prompts or items (that is, questions to solve or statements to choose amongst). Such items may be conceptualized as akin to large magnets, and the mind and its contents may be thought of as a large bin filled with myriad objects of varying sizes, structures, compositions and magnetisms (e.g., metal filings, plastic bits, iron chunks). Like a large magnet dragged along a workshop floor or plunged into a bin filled with various materials, a problem will intrinsically 'attract' characteristic knowledge elements. Certain prior knowledge elements will tend to be predictably drawn to particular problems (like metal filings to a magnet), whereas other bits will not (e.g., plastic). Thus, the analogy of a magnet (the item) plunged into the bin (the mind) and attracting particular elements (prior knowledge) may help to conjure a mental picture of what is happening when students read and begin to think about biological problems (see Fig. 1).

Many faculty naively hope that prior knowledge is absent from students' minds. That is, they would like their assessment items to exclusively attract accurate knowledge and not "naive ideas" such as scientific misconceptions. In line with such hopes, we teach students new knowledge assuming that it will be viewed as intrinsically more attractive than prior knowledge. Unfortunately, a century of educational research has shown that students' minds are filled to the brim with myriad types of knowledge that are significantly more attracted to our assessment items than we would like them to be (5, 6).

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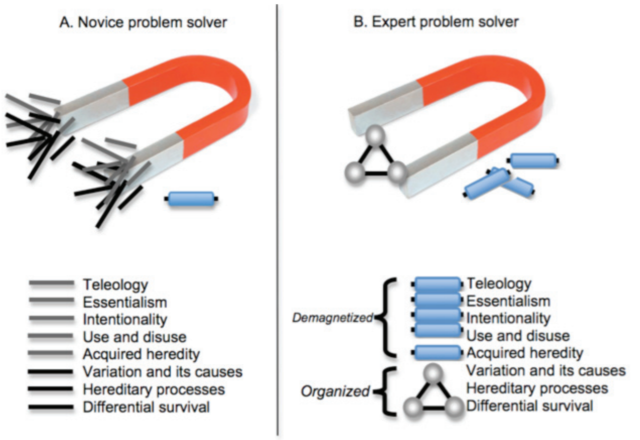

FIGURE 1. A magnet metaphor for problem-solving. In novices, many cognitive resources are highly attracted to problems. Such knowledge is often poorly organized and sensitized, leading to working memory overload. In experts, much naive knowledge has been appropriately sensitized to context (demagnetized) so that it is not attracted to problems but may be used in other contexts.

While teachers keep adding accurate scientific facts, laws and mechanisms to students' minds, there is a lot of intuitive and naive knowledge that has not gone away and remains highly valued. As a result, many faculty members are dismayed to find that assessment items (often from concept inventories) have drawn forth sets of inaccurate, naive or contextually inappropriate ideas (5). But this should hardly be surprising, as our classes and textbooks rarely help students manage their *prior* knowledge; that is, we often fail to help students "deactivate" knowledge that we *don't* want to be elicited by our assessment items (6). We perseverate in our emphasis that the new knowledge we provide is very important and useful — as if that's all that there is to choose from.

Because school science learning represents such a very small proportion of students' experiences with the living world (12), we should not be surprised that students' minds are filled with a host of everyday folk-biological notions (1). These include, for example, the belief that intentional (conscious) and teleological (goal-driven) actions guide the workings of biological systems (21). Students' working memory capacities have limited space; it is only possible to hold, manipulate and evaluate a finite number of knowledge elements (22). Consequently, our assessment items will predictably and unsurprisingly elicit these naive ideas or misconceptions intermixed with scientific knowledge. Naive prior ideas are most likely to be activated, leaving little room in students' working memory for other cognitive tasks (2). Thus, controlling knowledge activation emerges as a key issue in problem-solving.

When assessments fail to activate contextually accurate knowledge, it does *not* necessarily mean that such knowledge is absent (14). Indeed, just because one chose to eat cheesecake for dessert does not mean that knowledge was lacking that a fruit plate was healthier. Rather, it reflects the choice that was found more enticing in a particular context. Similarly, biology concept inventories appear to unambiguously reveal whether students' possess requisite knowledge or not. Yet in many cases such assessments may, in fact, be exposing the knowledge elements that students find most enticing in the contextual scenarios presented to them (14, 18). The contextual activation of knowledge thus emerges as a central problem-solving theme, but little research is available to inform our practice in this area.

It is not only the myriad types of "knowledge" (naive, scientific, and in-between) and their activation that are of significance to problem-solving, but also the underlying *organization* of this knowledge. A large body of research in many domains has revealed that experts tend to have well-organized, web-like funds of knowledge, filed and structured using key principles, rules and theories (19). In contrast, novices' knowledge tends to be list-like or haphazardly organized (19). Moreover, experts have in many cases re-filed and/or repurposed information into larger and more useful organizational schemas. What are the implications of these findings for problem-solving? Expert thinking during problem-solving entails: (a) effortless searches because of clear knowledge organization, (b) activation of larger chunks of well-organized ideas, and (c) exclusion of contextually burdensome naive ideas. Collectively, these attributes help to prevent the "clogging" of working memory during problem-solving (17, 2).

In contrast to the experts, student problem-solving is often characterized by the excessive activation of poorly organized information that must subsequently be sorted through and evaluated, frequently overwhelming working memory (2). But at this stage in expert problem-solving, organization is already complete (or nearly so), giving experts a head start (18); experts are ready to *use* their organized and appropriately "sensitized" prior knowledge so that they may begin to solve the problem at hand. Novices have much more work to do to even get to this point because much of their prior knowledge has not been appropriately organized or sensitized to context.

Given the chaotic nature of novice knowledge, separate solution "searches" will often lead to different knowledge elements being activated. Often, student responses to test or concept inventory items will be variable, given that so many possible knowledge elements have the potential to be attracted to instrument items. Student responses are often not reliable because they lack a stable organization scheme (17). Indeed, the "data dump" answers that we often suffer through are examples of items that have attracted too much information — nearly everything in sight or mind. In such cases, knowledge has not been sensitized to context. For example, despite the well-established fact that children and some college undergraduates find teleological, intentional and essentialistic notions highly attractive as biological explanations (21, 17), biologists do not. Biologists likely harbored such ideas in childhood, but they have "deactivated" such ideas during scientific problem-solving.

How do these findings relate to teaching biology? From the stance of problem-solving research, effective teaching may be more akin to "cognitive resource management" and context "sensitivity training" than supplementing prior knowledge with more and more scientific resources. Indeed, attempting to "dilute" or "bury" naive knowledge with scientific knowledge is a hopeless task, given the constraints of instructional time and vast scope of prior ideas. In contrast, working with — and trying to help students consciously *manage* — the knowledge that they already possess (and so often inappropriately apply) remains a novel approach. "Deactivating" prior knowledge inappropriate to scientific thinking is an essential prerequisite to biological cognition and problem-solving. But are such actions occurring in our classrooms?

Biologists, for example, have learned to "deactivate" teleological (goal-directed) and intentional (need- or desire-based) explanations in evolutionary contexts, but productively use such ideas in everyday life, where goals and needs *should* be brought to bear on human actions and social problem-solving (e.g., What goals will help me achieve tenure?). Thus, *context sensitivity* emerges as a central theme in scientific thinking and problem-solving. Aligning cognitive resources (i.e., knowledge) with problem contexts (e.g., aerobic vs. anaerobic; evolutionary trait gain vs. trait loss) is a central cognitive skill because it constrains problem search spaces and the types of information recruited during such searches (15). Student thinking will never be clear so long as prior knowledge is poorly aligned with contexts. Such context "sensitivity training" is so rarely witnessed in our nation's science classrooms.

Problem-solving, therefore, requires attention to three central topics: (a) problem contexts, (b) the mind's cognitive resources and their organization, and (c) the contextual activation of knowledge. The first step in helping students solve problems is to understand how the problem contexts and item features that they are likely to encounter differentially attract prior knowledge. Methodologically, finding this out is relatively straightforward (but laborious) (3). Designing so-called isomorphic items (same form and structure) with different concrete surface features, contexts or cues, and subsequently studying student responses to such item suites, helps to reveal what ideas item features elicit. Evolution test items using plants and animals, or the gain and loss of traits, elicit significantly different cognitive resources in undergraduate students despite nearly identical item contexts and structures (13). But many areas of the biological sciences remain unstudied in this regard.

Card sort tasks are another method for understanding how students conceptualize (internally represent) problems. Having students sort carefully designed suites of items placed on note cards into groups based on what they perceive to be item similarities and differences reveals how the prompts are envisioned internally (3). Often, experts and novices perceive items very differently and sort items differently. For example, in evolution problem-solving, novices often conceptualize problems from the standpoint of one individual organism — it may "need to" or "have to" change – whereas experts frame the problem from the standpoint of a population. Helping students to appropriately envision or represent the problem and recognize problem types, is a crucial but often neglected aspect of the curriculum.

Another commonly used method for revealing how students think about problems is the "think aloud" exercise. Here, students explain what they are thinking as they attempt to solve problems. Follow-up questions during the tasks may be used to clarify what students are thinking. Analyses of task transcripts may also provide important insights into how problems are both perceived *and* solved (3). Overall, many fruitful methods exist for studying biological problem-solving (3) and yet next to nothing is known about it in many subject areas within the biological sciences. Much work remains to be done.

Effective problem-solving instruction requires an understanding of how students think. But many ancillary tasks are also essential. Faculty must not solely present students with new knowledge, but must also take the time to help them organize and contextualize it. Ironically, biology textbooks and curricula reveal few clues as to how experts organize their biological knowledge, providing few guideposts for novices on their journeys toward expertise. In many respects, textbooks reinforce a scattered and fragmented conceptualization of biology, or one based on unhelpful organizational schemes such as "genetics" or "plants," which do little to foster effective problem-solving. Concept mapping is one useful tool for helping students organize and structure their knowledge around domain principles (such as energy transformation, natural selection, etc.) (20), yet it remains unpopular.

Sensitizing knowledge to particular contexts is an essential task for biology education. Indeed, when students block enticing (but contextually wrong) ideas out of working memory during problem-solving (e.g., teleology), they preserve cognitive space for searching for and evaluating alternative solutions (2). But most knowledge has contextual utility; it is useful in some contexts, but not in others. Many biologists are implicitly aware that particular problem contexts demand particular cognitive resources. But what, exactly, are these contexts and corresponding resources, and what knowledge should be sensitized to respond to cues indicative of such contexts? Students desperately need help recognizing these contexts, and receiving practice aligning their cognitive resources to such contexts. But next to nothing has been written about this in biology.

In closing, while we have the tools before us to better understand student problem-solving processes (3), we have yet to apply them to many biological subject areas (e.g., microbiology, genomics, physiology). Consequently, we do not yet understand why our assessment items tend to attract the cognitive resources that they do. A better understanding of problem-solving processes would allow us to help students organize, manage, sensitize, align and apply their cognitive resources to biological problems. Hopefully, this brief article will stimulate further work in this important but neglected aspect of biology teaching, learning and assessment.

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REFERENCES

1. **Atran, S. and D. Medin.** 2008. The native mind and the cultural construction of nature. MIT Press, Cambridge, MA.
2. **Baddeley**, **A.D.** 1986. Working memory. Oxford University Press, Oxford, UK.
3. **Chi, M.T.H.** 2006. Methods to assess the representations of experts' and novices' knowledge, p. 167–184. *In*: K.A. Ericsson, N. Charness, P. Feltovich, & R. Hoffman (eds.), Cambridge handbook of expertise and expert performance. Cambridge University Press, Cambridge, UK.
4. **Chi, M.T.H., P.J. Feltovich and R. Glaser**. 1981. Categorization and representation of physics problems by experts and novices. Cognitive Science **5:**121–152.
5. **D'Avanzo, C.** 2008. Biology concept inventories: overview, status, and next steps. BioScience **58:**1079-1085.
6. **Duit, R.** 2004. Bibliography: students' and teachers' conceptions and science education database. University of Kiel, Germany. http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html
7. **Dunker, K.** 1945. On problem solving. Psych. Monographs. **58:**270.
8. **Gabel, D. and D. Bunce.** 1994. Research on problem solving: Chemistry. *In*: D. L. Gabel (ed.), Handbook of Research on Science Teaching and Learning: a project of the National Science Teachers Association. MacMillan Publishing Company, New York, NY.
9. **Maloney, D.** 1994. Research on problem solving: Physics. *In*: D. L. Gabel (ed.), Handbook of research on science teaching and learning: a project of the National Science Teachers Association. MacMillan Publishing Company, New York, NY.
10. **National Research Council**. Committee on a New Biology for the 21st Century: Ensuring the United States Leads the Coming Biology Revolution. 2009. A new biology for the 21st century. National Academy Press, Washington, D.C.
11. **National Research Council.** Committee on Undergraduate Biology Education to Prepare Research Scientists for the 21st Century, Board on Life Sciences. 2003. BIO2010: Transforming undergraduate education for future research biologists. National Academy Press, Washington, D.C.
12. **National Research Council.** Committee on the Foundations of Assessment. 2001. Knowing what students know: the science and design of educational assessment. National Academy Press, Washington, D.C.
13. **Nehm, R.H. and M.Ha.** [in press]. Item feature effects in evolution assessment. J. Res. Sci. Teaching.
14. **Nehm, R.H. and I.S. Schonfeld.** 2008. Measuring knowledge of natural selection: a comparison of the CINS, an open-response instrument, and an oral interview. J. Res. Sci. Teaching. **45**:1131–1160.
15. **Newell, A., and H.A. Simon.** 1972. Human problem solving. Prentice-Hall, Englewood Cliffs, NJ.
16. **Novick, L., and M. Bassok.** 2005. Problem solving, p. 321–350. *In*: Holyoak, K.J. and R.G. Morrison (eds), The Cambridge handbook of thinking and reasoning. Cambridge University Press, Cambridge, UK.
17. **Plass, J.L., R. Moreno and R. Brunken** (eds.). 2010. Cognitive load theory. Cambridge University Press, Cambridge, UK.
18. **Reif, F.** 2008. Applying cognitive science to education: thinking and learning in scientific and other complex domains. MIT Press, Cambridge, MA.
19. **Reif, F. and J.I. Heller**. 1982. Knowledge structure and problem solving in physics. Edu. Psychologist. **17**:102–127.
20. **Science Education Resource Center**. Developing concept maps. Accessed online June 3, 2009 at: http://serc.carleton.edu/introgeo/assessment/conceptmaps.html
21. **Sinatra, G.M., S.K. Brem and E.M. Evans**. 2008. Changing minds? Implications of conceptual change for teaching and learning about biological evolution. Evo. Edu. Outreach. **1**:189–195.
22. **Staver, J. R.** 1986. The effects of problem format, number of independent variables, and their interaction on student performance on a control of variables reasoning problem. J. Res. Sci. Teaching. **23**:533–542.
23. **Stewart, J. and R. Hafner.** 1994. Research on problem solving: Genetics. *In*: D. L. Gabel (ed.), Handbook of research on science teaching and learning: a project of the National Science Teachers Association. MacMillan Publishing Company, New York, NY.