Problem- and Case-Based Learning in Science:

Distinctions, Virtues and Caveats

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Abstract

What features characterize different versions of case-based and problem-based learning, as a suite of instructional strategies? How does each difference relate to student motivation and/or learning? Here we profile such factors as level of student autonomy, scope of problem, historical-type cases, focus on content, skills development or nature-of-science understanding, collaboration, number of interpretive perspectives and, perhaps most importantly, knowledge-generating v. knowledge-applying scenarios.

Keywords: case-based learning, problem-based learning

> A leader who gives trust earns trust.
> His profile is low, his words measured.
> His work done well, all proclaim,
> ‘look what we've accomplished!’
> –Lao Tsu, *Tao Te Ching*

Problem-based learning (PBL) and case-based learning are at least as old as apprenticeship among craftsmen. In recent years, however, they have emerged as potentially powerful teaching tools in reforming science education. One especially notable feature is the prospect of teaching thinking skills and nature of science, in addition to content. While this family of instructional styles spans a variety of approaches, various advocates often present their own characterizations as the exclusive method (Barrows, 1994; Savery, 2006), easily fostering confusion. Most notably, PBL Here we forsake programmatic labels and taxonomies in the interest of clarifying some important distinctions or dimensions and how they are relevant to various teaching objectives. While similar surveys may be found elsewhere (Herreid, 2007; Hmelo-Silver, 2004; Lundberg, Levin and Harrington, 1999), we introduce many significant distinctions not addressed in those accounts, relevant both to teachers who are adopting and adapting PBL and to educational researchers who wish to investigate PBL in science education.

Focusing on differences in pedagogical approaches encourages one to think more rigorously about educational aims. For example, is knowing content the ultimate aim? To what degree is understanding scientific practice and/or its cultural contexts also important? What are the aims regarding analytical or problem-solving skills? —Or learning how to learn beyond the classroom? Is student motivation, or engagement in learning, a goal? Does one hope to shape student attitudes about the value or authority of science? —Or recruit more students into scientific careers, or promote greater gender or ethnic balance? What role is afforded to student autonomy, either in shaping one's own learning trajectory or as a product, reflecting student competency? Possible outcomes range from traditional conceptual content to skills and affective properties. Different methods will foster different outcomes. Our goal is to foster aligning desired aims with appropriate strategies or teaching tools. The significant major distinctions (explored below) are summarized in Table 1.

Case-based (Case study-learning) / Decontextualized

Most science textbooks present decontextualized, or abstracted, knowledge. Cases, however, situate the knowledge *in real-world contexts*. Here, the cases provide the *primary occasion for learning*, rather than serve secondarily as illustrations or applications. The cases are not supplemental sidebars, but are integral to the structure of learning.

Contextualization fosters two major effects. First, it *enhances learning* by providing associations that facilitate memory storage, retention and retrieval: the knowledge is more meaningful. Second, it also helps *motivate learning*. Cases convey that the knowledge is relevant or useful, sometimes by showing its 'human' dimension. Such contextual and human connections seem especially important (in today's culture) in fostering interest among women/girls and minorities, as well as among non-majors. Such benefits indicate the need for careful selection of cases to fit particular groups of students, their contexts (age, locality, culture), interests and levels of background knowledge.

Case-based learning, however, may not convey well the comprehensiveness or organization of knowledge conveyed in more didactical approaches. That is, the formal structure of a substantial domain of knowledge may not be evident when knowledge is accumulated by piecemeal sampling. (For example, a case may profile only a few—not all—organelles in the cell, or a focus on the nitrogen cycle alone may forsake a broader awareness of other mineral cycles and their general role in ecosystems.) Nevertheless, a carefully constructed curriculum may use complementary cases to cover standard curricular content (see Schwartz et al., 1994). On the other hand, some evidence indicates that learning occurs primarily, or most vividly, through exemplars (Kolodner, Hmelo, &Narayanan, 1996; Gentner, Loewenstein, &Thompson, 2003; Gentner and Colhoun, 2008). One case or example serves as a model, or paradigm, for interpreting other similar cases (Kuhn, 1972, pp. 23, 187-191).

For more on the benefits and limits of case-based learning generally, see Barnes, Christensen, and Hansen (1994) and Lunberg, Levin, and Harrington (1999). For sample textbooks using a case structure, see (at the undergraduate level) Postlethwait and Hopson (2003), Schwartz et al. (1994); and (at the secondary level) Leonard, Penick, and Speziale (1998/2008) and American Chemical Society (2006).

Problem-based / Narrative

Another way of providing context and motivation is by *posing problems* for students to solve. Typically, such problems are rooted in cases (although they need not be, or the case itself may be quite minimalistic). Nor is all cased-based learning problem-based. Cases may function merely as narratives, or as a setting for knowledge. This may so even where a story (of an important historical discovery, say) helps students learn about how a scientist encountered and solved a problem.

In problem-based learning, the problem is *posed to the student,* who then takes an active role in solving it. Active learning —itself expressed in various ways— is widely recognized as enhancing motivation as well as depth and persistence of learning (Bonwell and Eison, 2001; Michael, 2006) (see also section on autonomy below). The introduction of cogent problems thus tends to amplify the basic virtues of using cases themselves — provided that the problems are framed in ways relevant to the student. Almost any declarative knowledge can be rephrased as a question or problem. However, just as a case must be judiciously selected, a problem must be properly framed and contextualized if it is indeed to be motivational. The teacher who begins, ‘Today we study the pancreas; now, what is a pancreas?’, does not engage student interest. Indeed, students can easily spot a 'rhetorical problem' or pseudo-problem. 'Cookbook' problem cases are no better than 'cookbook' labs. A teacher who needs to institute substantial external motivators for students to complete work, for example, has probably not found the proper problem to inspire active, student-centered learning. One may consider framing and contextualizing problems as one of the primary instructional skills for this mode of teaching.

In addition, engagement with problems introduces a deeper layer of thinking: about the generation of knowledge, about the nature or quality evidence, about reasoning, etc. It may foster a habit of curiosity or of questioning assumptions. Problems tend to promote reflective thinking.

Cases may certainly combine narrative and problems. One effective method ‘interrupts’ a story or punctuates it with a series of well contextualized problems (Hagen, Allchin, & Singer 1996; Herreid, 2005).

For more on the benefits and limits of problem-based learning generally, see Duch, Gron, and Allen (2001), Dochy, et al. (2003), Hmelo-Silver (2004), Major and Palmer (2005). Also relevant is the substantial literature on the role of anomalies, 'discrepant events' and 'cognitive dissonance' in stimulating learning.

Content-focused / Skill-focused / Context-focused

The pedagogical function of cases or problems can vary. In a widely used model (Barrows 1986), the problem is considered primarily a vehicle for learning *content*, which ultimately answers the given question or solves the problem at hand. In other cases, the problem engages students in practicing or developing *problem-solving skills* through first-hand experience. (Here, one needs to provide a framework for students to learn new skills, not just exercise existing abilities.) Both styles, appropriately adapted, may also help foster deeper *understanding of the nature of science*, or of scientific practice, of how science works or of the context of science, broadly speaking (see more below). However, learning about the nature of science must be both *explicit* and *reflective* (Craven, 2002; Schwartz, Lederman, & Crawford, 2004; Scharmann, Smith, James, & Jensen, 2005; Seker and Welsh, 2005). That is, one must pose problems specifically about the nature of science and engage students in discussion. These three aims are not necessarily mutually exclusive. Some cases may well integrate these (for example, see Hagen, et al., 1996; Allchin, 2010).

The ultimate aim of education will be reflected in—and communicated to students most vividly through—the forms of evaluation. Initiating efforts to teach problem-solving skills or understanding of the nature of science may well require a shift in modes of assessment and/or grading standards. Teachers will surely benefit in any event by reflecting how the learning objectives of their courses are coupled to the ways they ask students to demonstrate or exhibit such learning.

Knowledge-generating / Knowledge-applying

The problems students encounter can be of two general kinds: they can *use knowledge that already exists* to solve or interpret a problem, or they can involve (or model) research that *generates new knowledge*. ('New', here, is defined relative to the student.) Repairing a car engine is quite different from designing one. Diagnosing a patient with an already documented disease is quite different from studying the etiology of a wholly new disease. The terms 'investigation', 'research' or 'problem-solving' are all potentially ambiguous, denoting either alternative. But the processes of solving problems and justifying conclusions are substantially different and should be made clear. Students should ultimately appreciate the distinction: crudely akin to the difference between technology and science.

Similarly, students might also appreciate the difference in cognitive processes: rationalizing a conclusion is different from justifying a new discovery. The former is highly susceptible to error through confirmation bias (Nicherson, 1998).

If the learning objectives emphasize content and/or its cultural contexts, one can ostensibly focus on applications alone. Students will draw on a known repertoire of knowledge. (This is typical of problem cases or scenarios in medicine, law, business, engineering, applied ethics, and other professional training—where PBL and CBL first emerged most prominently. All are based on precedent, even if the cases invite creatively recombining extant ideas.) However, if one wants students to learn about the process of science or research, the problems must be about developing knowledge: exploring genuine unknowns (for the student) and creating knowledge, not merely finding and interpreting known facts. Learning about the role of empirical evidence as a foundation of scientific knowledge is critical to shaping one dimension of epistemological belief: whether the source of authority in knowledge is empiricism or omniscience (Schommer, 1990).

In our view, the knowledge-generating/knowledge-applying distinction may be the currently least appreciated distinction profiled here, fostering major misleading or erroneous impressions about the aims, benefits or structure of problem-based learning *in science education*.

Historical / Contemporary

Cases may be historical or contemporary, or completed abstracted from any historical context. Here, the relevant dimension denoted as 'history' is largely whether the problem being considered has been solved or remains unsolved: what Latour (1987) denoted as ‘ready-made-science’ versus ‘science-in-the-making’. The status of the problem solution is critical to the possible lessons that can be learned.

Contemporary cases often appeal to students by being relevant, ‘current,’ or fashionable. They convey that science is happening now, affording a greater sense of immediacy or authenticity (Wong, Hodson, Kwan, & Yung, 2008). Students may even encounter some cases in the news—relevant just to the degree that students seriously attend to current events. Current problem cases that focus on the context of science can offer rehearsals for participating in personal decision-making or social policy in future life., although care must be taken to enrich the learning rather than merely elicit and reinforce existing perspectives.

Historical cases have their own virtues (Conant, 1947; Hagen, et al., 1996, v-vii; Allchin, 1997, 2010). First, the benchmark content knowledge in standard science curricula originated long ago. The strategic pedadgogical constructivist will thus look to history for clues about how such concepts may be ‘constructed’ from earlier facts and perspectives, as well as how they may be alternatively conceived or criticized. Imagine the sense of validation when informing a student that the concept s/he just developed is the same concept discovered earlier by a famous scientist! Second, historical narratives are prime opportunities for teaching about scientific practice. Where learning objectives include process of science skills, cases rendered *in historical context* (say, through the eyes of a past scientist) recreate ‘science-in-the-making’. Students may participate in (re)generating knowledge at a conceptual level corresponding to their own.

Third, history seems essential for conveying certain lessons about the nature of science, most notably about cultural bias in scientific ideas, conceptual change, uncertainty and error (or how scientific knowledge— new findings, in particular—can be uncertain and/or provisional) (Solomon, Duveen, Scot, &McCarthy, 1992; Irwin, 2000). 'Tentativeness of scientific knowledge', for example, has been a pervasive learning goal in science education for many decades (Lederman, Wade, & Bell, 1998), and constitutes a significant dimension of epistemological belief—the stability of scientific knowledge (Schommer, 1990). To learn about conceptual change, however, one ideally engages in and experiences the change. A case properly contextualized in history, not rationally reconstructed, is essential (Allchin, 1996, 2004). To enable informative contrast of a reasonable 'before' with a possibly unexpected 'after,' the problem-solving episode must be past and amenable to retrospective analysis. In a similar way, to appreciate gender or racial bias or other ways that cultural perspectives may sometimes become blindly naturalized in science, one must be at a relatively remote vantage point to see the culture as culture. History and historical perspective are indispensable for such nature of science lessons.

Finally, historical cases tend to change less with time. This year's 'hot' topic will be 'passé' soon, and the work assembling and refining a new contemporary case will start all over again. Cost/benefit ratio of teacher preparation may be considered.

Open-ended / Close-ended

Does the problem have one (hidden) solution or many possible solutions? That is, in terms of the student's problem-solving, is the process close-ended or open-ended? (Or, in terms of the literature on creativity, is the cognitive process convergent or divergent?) Each type shapes student motivation and understanding of science in substantially different ways (Cliff & Nesbitt, 2005). A problem for which there is a single known solution places students in a vulnerable position, much like a teacher that 'fishes' for the right answer in a lecture class: such situations tend to alienate students (expressed as silence or acquiescence) and thus diminish the role of problems as motivators. Some students, of course, revel in 'puzzle-solving' (Kuhn, 1972); others feel threatened. Close-ended problems, alas, can also foster cheating or rationalization (working backwards from a target solution), quite the opposite of what is intended. Where science content and/or information-finding skills are the aim, PBL may tend towards close-ended problems. But it need not. In biology, in particular, problems might be re-framed and answered at different organizational levels simultaneously. Close-ended problems may also be used to help develop problem-solving or analytical skills—but one then needs to carefully tailor assessment accordingly, to promote and reward those skills, rather than just yielding 'the right answer'. Finally, close-ended problems tend to support a naive epistemology of knowledge as stable and authority based.

Open-ended problems, by contrast, tend to promote more creative skills and thus motivate a wider variety of students. Such types of problems also seem essential for developing an epistemological understanding that knowledge is generated empirically and that science, while evidence-based, is contingent, sometimes underdetermined and provisional. Historical problems, ostensibly already solved, would seem to be closed-ended, but they can be situated in their original context, in an open-ended framework where process and reasoning is more important than any specific conclusion. (Indeed, it may be the teachers who face the greater challenge, trying to temporarily blind themselves to known outcomes in order to focus on process alone.)

Real cases / Constructed cases or problem scenarios

The cases that contextualize knowledge may be drawn from real life examples, or they may be imaginatively assembled for an educational context. Constructed cases may be created to fit particular needs. They may be as simple or complex as one wants. They may be freely edited and streamlined to highlight core concepts or learning aims. They are more readily generalized. On the other hand, such cases often carry an implicit aura of artificiality and risk diminishing their motivational value if the student feels that they are contrived.

Real cases, by contrast, are indeed authentic, although they are often 'messy'. Still, the ‘messiness’ can be an asset. First, the unique constellation of particulars can help demonstrate the sometimes unexpected ways in which different factors in science interact (sources of funding, personality, happenstance, disparate facts, etc.). Second, they can help students learn how to negotiate in a complex world, where one must sometimes recognize and tease out the relevant variables on one's own. Third, they may also be critical to shaping another basic dimension of epistemological belief: that *the structure of knowledge can be complex*, not always simple (Schommer, 1990).

At an impressive extreme, students — even non-science majors or K-12 students — might participate in ongoing research. While tasks might not be any more demanding than gathering data, students may certainly understand the context of the work, see closely how it is structured, and take pride in contributing to developing original scientific knowledge.

Well defined problems / Ill defined problems / Unspecified problems

Only some problems in the world (perhaps quite few) are well defined. A complete education thus helps develop skills in *articulating ill-defined problems* (Jonassen, 1997). One may also help foster skills in *posing problems* (Jungck, 1985; Gonzales, 1998). However, problem-solving skills themselves may well be developed where the problem is already well defined and appropriately ‘motivated’. Of course, a problem may be redefined or dissolved: that may be part of the ‘solution’ (concluding that the problem was ill framed or ill conceived at the outset).

Ill-defined problems are typically a significant component in medical school problem-based education, reflecting the central role of diagnosis in clinical medicine—that is, of finding, characterizing and identifying how or why the patient is not well. By contrast, cases used in business schools or law schools tend to be more well defined, reflecting the custom of addressing client-based problems. In either case, refining or redefining a given problem— or even dissolving it entirely—may well enter the process en route to a 'solution,' as found in scientific research as well.

Problems may also be unspecified in advance, contingent on students posing them (see section on autonomy below).

'Paper' problem-solving / Investigative

Conventionally, classroom lab exercises may be 'wet' or 'dry'. That is, they may be done materially in a laboratory or intellectually on paper—or today, also virtually/electronically via computer simulations. While almost all commentators acknowledge the value of 'hands-on' lab work, costs, time and/or other resources may be limiting; hence, simulated alternatives can be valuable (Yaron, Karabinos, Lange, Greeno, & Leinhardt, 2010). Computers, in particular, offer unprecedented opportunties through savings in computational time and access to vast data resources, unthinkable in education not long ago. In some cases laboratory activities may be effectively inserted into the course of a case study that is otherwise completed on paper. Care should be exercised, of course, to articulate for students the difference between *investigative labs* (with genuine unknowns) and *demonstrations* or *observational activities* (which may prove valuable for other reasons, even if yielding explicitly expected results).

A special category of investigative problem-based learning involves *rich data sets*—pre-established measurements or results that are vast enough for exploration, yet (in an educational context) have known/identifiable boundaries. Students may thus pose original problems for which the data set may provide an answer. At the same time, one might entertain such enterprises mindfully. Some students may not share the instructor's or other student's enthusiasm for investigation, even if they are given the freedom to frame their own question. Such students may thus become overwhelmed, discouraged or even resentful.

Single-perspective / Multiple-perspective

Cases or problems may well be addressed cogently from a single perspective, such as a dilemma-plagued agent or a renowned historical scientist. Simple cases limit the challenges and streamline the process of problem-solving, perhaps appropriate in initial stages of learning. Some cases are problematic, however, precisely due to different interpretations of the same problem. Here, a student learns, first, that problem-solving or research may not be exclusively individual or univocal: that is, not according to some universal linear algorithm (such as 'the' scientific method). Yet multiple perspectives may also prove an asset, as well. Other viewpoints may reveal alternative solutions not readily envisioned within a particular mindset or background. One of the greatest benefits of simple discussion may be exposing students to other perspectives and thereby deepening their awareness of alternatives and (one hopes) broadening their repertoire of ways of thinking. Students themselves often report how much they learn simply from listening to how other students view the same 'facts' differently.

Cases with multiple perspectives offer opportunities to teach about social dimensions of developing knowledge and solving problems. Social epistemology, for example, has been highlighted recently by philosophers of science (Longino, 1990; Goldman, 1999, 2002; Solomon, 2001), as well as by science educators (Osborne, 2010). When varying perspectives interact, one can enhance ways to analyze a problem or imagine its solution. Here, one may guide students in learning discoursive skills, such as active listening, critical to such forms of social level analysis. Even criticism may have a positive role in exposing weak assumptions or increasing rigor of evidence, highlighting the value of tolerating criticism as an emotional or attitudinal skill. In yet other cases, where interpretations conflict, students may learn skills in negotiating solutions or finding creative ways to accommodate apparently incompatible views (Fisher, Ury, &Patton, 1991). Thus, case-based or problem-based learning may adopt the familiar forms of a debate or role-play simulation (for well developed complex examples, see Dunn, Driscoll, Siems, & Karnak [2009] on Darwin and the Royal Society's Copley medal in 1862; Allchin [2009a] on the Galileo Trial in 1633; Allchin [2009b] on a Presidential commission on pesticides in 1963; and Montgomery [2010] on glacial geology in 1843). Role-play activities provide students additional grounding through a concrete perspective for interpreting a case or problem. Unfamiliar roles (or sides in a debate) can also enhance appreciation of alternative perspectives. Even where students continue to work primarily on their own, however, one may still find a fruitful learning role for exchange of multiple perspectives.

Collaborative / Individual

Like other forms of education, case-based or problem-based learning may be either individual, collaborative or cooperative. For more on the benefits and limits of cooperative learning in general, see Johnson and Johnson (1991).

Collaborative problem-solving often involves special skills, such as brainstorming and supportive critique, which ideally become part of instruction. Collaboration should be further distinguished from 'cooperation', or 'group work', where the product does not document or acknowledge the individual contributions of each group member (Panitz, 1996). That is, collaborative work maintains individual accountability, whether each student is responsible for a full product (case analysis, problem solution report, essay, exam, etc.) or for a discrete, identifiable portion of a final work product.

Collaboration may be exercised on several levels — in pairs, in small teams (say 3-6), or even in large groups. Some exercises, such as a model UN, model Congress, or simulated meeting on global climate change may include dozens or hundreds of students. Role-play simulations (mentioned above), especially, can allow for creative synthesis among many unique student contributors within the same class, and thus exhibit the power of collaborative engagement. To help illustrate the value of collaboration, fragments of information for solving a complex problem may well be artfully distributed among different roles.

While collaboration offers many potential benefits, working jointly on one problem may be at odds with the motivational aim associated with an individual pursuing a problem of personal relevance. Even if there is a consensus or joint decision-making process, the shared problem may not engage all participants equally. Role-playing may be an effective pedagogical strategy for fostering a sense of personal responsibility through a vicarious 'as-if' scenario.

Scope of Case/Problem

The scope or magnitude of the case or problem itself may vary substantially. For the sake of sorting, it may be appropriate to label three simple levels. First are vignettes or short stories. These are the type that can easily be inserted in a lecture format, say, and probably focus on only one relatively narrow question or problem. Second are one-day lessons. These might include a series of short problems, or one problem that can be conveniently solved (and neatly packaged) in one class period. Finally, there may be major projects that extend over several class periods, weeks, or the bulk of a semester where the complexity of the problem allows (for examples, see White [1992], based on hemoglobin in biochemistry, Tewksbury [1999], based on geology and the Aswan Dam, or Klassen [2006], based on the electrodynamics of the Transatlantic Cable). To the degree that science is complex, and that education implicitly frames expectations beyond the classroom, teachers may well be encouraged to include some complex case studies or problems at some point in their courses, as an indication of the 'real world' and as an occasion for developing interpretive and organizational skills appropriate to such situations. One may also structure a series of lessons through a lineage of problems—as is frequently already done in teaching transmission genetics, atomic models, or the wave/particle nature of light (for example the biology text by Mix, Farber, & King, 1996, is organized on this principle).

Scaling problems appropriately also has an important affective dimension, relevant to the long-term motivational context. In introducing problem-based learning, especially, one should aim to create initial successful experiences to promote attitudes towards further work (or at least averting a sense of failure that discourages future effort!). Coping with perceived 'failure' as an outcome—or as a potential opportunity for learning—may itself be a goal, but may well be reserved for more 'advanced' levels.

Levels and Dimensions of Student Autonomy

Perhaps most important, case-based or problem-based learning tends to resonate strongly with the pedagogical ideal of *student-centered learning* (and, by correspondence, *egoless teaching*). At one level, this merely expresses a professional ethic of *respect for students*. At another level it underscores the observation that what teachers teach is not necessarily what learners learn. Genuine learning—that is both meaningful and long-lasting—needs to attend (at least) to students' cognitive orientations, especially their motivations to learn. Learning is most effective when students adopt responsibility for their own learning. Montessori educational philosophy classically underscores this dimension in early childhood education. Problem-based learning is perhaps the educator's primary tool for fostering such a fruitful learning environment.

Education ultimately strives (ideally) to *prepare students to function independently,* or *autonomously*: to use or apply the knowledge they acquire, to solve problems, and to continue to learn on their own. Such responsibility will likely develop gradually. The educational setting may thus structure growing levels of student autonomy, building increasing independence. Consider, for example, a series of challenges posed by Charles Kugler to his introductory college biology students. First, they must explain why a particular experimental control is appropriate in a given lab. One lab later, they must identify the appropriate control themselves. In the next lab, they select their own variable to investigate *and* the corresponding control. Finally, they must assemble a research proposal, which is peer reviewed in class—and the 'winner' becomes the activity for the whole class. Here, autonomy is elegantly expanded stepwise.

Students also need support or guidance in adopting new responsibilities. Developing autonomy has affective as well as cognitive dimensions. Giving problems to students with little additional guidance can easily alienate students and sour the teacher-student relationship fundamental to continued learning. Equally problematic are projects where students sail through cases using known strategies, not learning anything new: problems should challenge students. Instruction may well begin with *modeling skills*: providing behavioral exemplars that can be readily applied to simlar cases or through simple analogy. In addition, problem-solving activities should be scaffolded, or given an incomplete but supportive structure. Teachers may note that problem-solving in knowledge-generating cases may simultaneously yield a form of basic epistemological learning: that is, coming to understand that the ability to learn occurs incrementally, based on learning how to learn, and that it is not fixed (or innate) (Schommer, 1990).

Effective instruction will thus mindfully arrange different forms of autonomy:

- selecting the problem

  Student selection of the problem may contribute to the sense of ownership that makes the learning exercise personal. But it need not. Some problems may be justified as of general enough interest, or in a framework of public responsibility.

  One danger, here, is that while the student may choose the problem, s/he generally does not have the option of *not* choosing a problem (say, because there is nothing of intrinsic interest). Here, the goal of using context as a motivator is lost.

- defining the (ill-defined) problem
- securing relevant background information and resources

  Does the teacher ever answer a question with anything other than another question? Depending on the local aims, the teacher may provide plentiful background information, including standard lectures, or the student may be responsible for finding all such information (perhaps with guidance at the level of *how* to find that information), or there may be some intermediate form of support, suitable to the aims and occasion at hand.

- articulating methods/designing investigations
- solving the problem

  Problem-solving actvities may be teacher-guided or student-directed. Guided work may be more important than earlier imagined (Mayer, 2004; Minstrell and Kraus, 2005), at least initially. Again, one responsibility for the instructor is to be familiar with (or pre-assess) student abilities, to frame the problems at an achieveable level. Even where students have autonomy, the teacher has a critical role as advisor, coach, and possibly resource guide.

- facilitating discussion

  Where problem-solving is collaborative, an important role is facilitating discussion. Teachers may adopt this role initially, again to model appropriate skills, or to monitor and adjust progress along the way. Alternatively, students may be encouraged to develop such skills, sometimes in small groups.

- negotiating solutions

  An important dimension of collaborative work is developing consensus where interpretations differ, especially by appeal to evidence and reasoning, rather than external authority (the Instructor, say, or the 'Right Answer'). Persuasion, argumentation, active listening, revising, and accomodating conflict creatively are among the skills to be addressed in a complete problem-solving education (Osborne, 2010).

Summary

Instructional strategies labeled as 'problem-based learning' and 'case-based learning' embrace a wide range of overlapping, but independent methods. We advocate being aware of the variants, rather than trying to enforce strict definitions or 'best practices'. Instead, the educator should be mindful of the individual features or dimensions of this family of related instructional methods (Table 1). The aim, presumably, is to enrich student learning in various learning contexts, not to defend, promote or criticize any particular school of teaching.

In addition, educational research on PBL or case-learning needs to articulate the relevant variables along with their corresponding effects. Much research on efficacy of PBLis multivariate and fails to clarify the relationship between the particular dimensions of teaching noted above and particular effects for learners (for example, motivation, attitudes towards the subject, autonomy in problem-solving, reductionistic problem-solving biases, nature-of-science understanding, etc.).

Most important, it may be prudent to acknowledge that case- or problem-based learning approaches are not a panacea for any deficit in science education. They are tools. When used appropriately, a tool can be useful. We advocate the prudent use of appropriate tools for particular contexts. That may well include a role for lecture in conveying certain forms of knowledge, especially its overall structure and organization.

Having acknowledged the limitations, however, let us also underscore the opportunities offered by case-based and problem-based instructional methods. We thus encourage teachers to include them in their 'toolkit' and look actively for occasions where they will enhance student learning, both motivationally and in depth of understanding. For example, one can hardly learn problem-solving skills without engaging problems. *Posing problems* for students to solve thus seems a central tool for much analytical and creative skill development. Likewise, participation in *knowledge-generating* cases, whether direct or vicarious, seems integral to learning or appreciating the nature of scientific research. Similarly, *historical cases* seem important to learning certain core nature of science themes. Finally, to develop more sophisticated epistemological beliefs—foundational to continued and autonomous learning— students need exposure to *complex cases* (structure of knowledge), *historical cases* (stability of knowledge), *knowledge-generating cases* (source of authority in knowledge), and *successful experience in problem-solving* (nature of the knower).

We hope to sensitize case-users to be alert to the style of instruction that is used or implied in each case they encounter. We also encourage those who present cases or archive them for public use to fully characterize their cases along these dimensions, to assist users in finding appropriate cases or interpreting their prospective uses.

References

Allchin, D. (1996). How *not* to teach history in science. *Journal of College Science Teaching*, 30, 33-37. Reprinted in *The Pantaneto Forum* 7 (July, 2002). URL: www.pantaneto.co.uk/issue7/allchin.htm.

Allchin, D. (1997). The power of history as a tool for teaching science. In A. Dally, T. Nielsen and F. Reiß (eds.), *History and Philosophy of Science: A Means to Better Scientific Literacy?* (pp. 70-98). Loccum: Evangelische Akadamie Loccum. Also see URL: ships.umn.edu/tool.htm.

Allchin, D. (2004). Pseudohistory and pseudoscience. *Science & Education*, 13, 179-195.

Allchin, D. (2009a). *Debating Galileo's* Dialogue*: The 1633 Trial*. Minneapolis, MN: SHiPS Resource Center. URL: galileotrial.net.

Allchin, D. (2009b). *Debating Rachel Carson's* Silent Spring*: The President's Committee on Pesticides, 1963*. Minneapolis, MN: SHiPS Resource Center. URL: pesticides1963.net.

Allchin, D. (2010 [forthcoming]). From rhetoric to resources: New problem-based historical cases for nature of science education. *Science & Education*.

American Chemical Society. (2006). *Chemistry in the Community*, 5th ed. New York, NY: W.H. Freeman.

Barnes, L.B., Christensen, C.R. & Hansen, A. (1994). *Teaching and the Case Method*, 3d. ed. Boston, MA: Harvard Business School Press.

Barrows, H.S. (1986). A taxonomy of problem-based learning methods. *Medical Education*, 20, 481–486.

Barrows, H.S. (1994). *Problem-Based Learning Applied to Medical Education.* Springfield, IL: Southern Illinois Univ. Press.

Bonwell, C. & Eison, J. (1991). *Active Learning: Creating Excitement in the Classroom.*

AEHE-ERIC Higher Education Report No.1. Washington, DC: Jossey-Bass.

Butler, R., Inman, D. & Lobb, D. (2005). Problem-based learning and the medical school: another case of the emperor's new clothes? *Advances in Physiology Education*, 29, 194-196.

Cliff, W.H. & Nesbitt, L.M. (2005). An open and shut case? Contrasting approaches tp case study design. *Journal of College Science Teaching* 34(4), 14-17.

Conant, J.B. (1947). *On Understanding Science*. New Haven, CT: Yale Unviersity Press.

Craven, J.A. (2002). Assessing explicit and tacit conceptions of the nature of science among preservice elementary teachers. *Int. J. Sci. Educ.*, 24, 785–802.

Dochy, F., Segers, M., Van den Bossche, P., & Gijbels, D. (2003). Effects of problem-based learning: a metaanalysis. Learning and Instruction, 13, 533-568.

Duch, B., Gron, S. & Allen, D. (2001). *The Power of Problem-Based Learning.* Sterling VA: Stylus Publishing.

Dunn, E., Driscoll, M., Siems, D. & Karnak, D. (2009). *Darwin, the Copley Medal and the Rise of Naturalism*. Longman.

Fisher, R., Ury, W. & Patton, B. (1991). *Getting to Yes*, 2d ed. New York, NY: Penquin.

Gentner, D. & Colhoun, J. (2008). Analogical processes in human thinking and learning. In B. Glatzeder, V. Goel & A. Muller (eds.), *Towards a Theory of Thinking* (pp.35-48). Berlin: Springer.

Gentner, D., Loewenstein, J. & Thompson, L. 2003. Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology*, 95, 393-408.

Goldman, A. I. 1999. *Knowledge in a Social World*. Oxford: Oxford University Press.

Goldman, A. I. 2002. *Pathways to Knowledge: Public and Private*. Oxford: Oxford University Press.

Gonzales, N.A. (1998). A blueprint for problem posing. *School Science and Mathematics* 4, 448-456.

Hagen, J., D. Allchin & F. Singer. 1996. *Doing Biology*. Glenview, IL: Harper Collins.

Herreid, C.F. 1998. Sorting potatoes for Miss Bonner. *Journal of College Science Teaching*, 28, 236-239.

Herreid, C.F. 2005. The interrupted case method. *Journal of College Science Teaching,* 35(2), 4–5.

Herried, C.F. 2007. *Start with a Story*. Arlington, VA: National Science Teachers Association Press.

Hmelo-Silver, C. E. 2004. Problem-based learning: What and how do students learn? *Educational Psychology Review,* 16, 235-266.

Irwin, A. R. 2000. Historical case studies: teaching the nature of science in context. *Science Education,* 84(1), 5-26.

Johnson, D.W. & Johnson, R.T. 1991. *Learning Together and Alone*. Englewood Cliffs, NJ: Prentice Hall.

Jonassen, D.H. (1997). Instructional design models of well-structured and ill-structured problem-solving. *Educational Technology Research and Development* 45, 65-94.

Jungck, J. (1985). A problem-posing approach to biology education. *American Biology Teacher* 47, 264-266.

Klassen, S. 2006. The application of historical narrative in science learning: The Atlantic cable story. *Science & Education,* 16, 335-352.

Kolodner, J.L., Hmelo, C.E. & Narayanan, N. H. 1996. Problem-based learning meets case-based reasoning. In D.C. Edelson and E.A. Domeshek (eds.), *Proceedings, 1996 International Conference on Learning Sciences* (pp. 188-195). Charlottesville, VA: American Association for Computers in Education.

Latour, B. 1987. *Science in Action*. Cambridge, MA: Harvard University Press.

Lederman, N. G., Wade, P. & Bell, R.L. 1998. Assessing understanding of the nature of science. *Science & Education,* 7, 595-615.

Leonard, W.H., Penick, J.E. & Speziale, B. (1998/2008). *BioComm: Biology in a Community Context.* Cincinatti, OH: Thomson; Armonk, NY: It's About Time, Herff Jones Education Division.

Longino, H. (1990). *Science as Social Knowledge*. Princeton, NJ: Princeton Univeristy Press.

Lunberg, M.A., Levin, B.B. & Harrington, H.L. (1999). *Who Learns What from Cases and How?* Mahwah, NJ: LEA Publishers.

Major, C.H. & Palmer, B. (2001). Assessing the effectiveness of problem-based learning in higher education: lessons from the literature. *Academic Exchange Quarterly,* 5(1).

Mayer, R. (2004). Should there be a three-strikes rule against pure discovery learning? The case for guided methods of instruction. *American Psychologist,* 59, 14–19.

Michael, J. (2006). 'Where's the evidence that active learning works? *Advan. Physiol. Edu.,* 30, 159-167.

Minstrell, J. & Kraus, P. (2005). Guided inquiry in the science classroom. In M. Suzanne Donovan & John D. Bransford (Eds.), *How Students Learn: History, Mathematics, and Science in the Classroom* (pp. 475-513). Washington, DC: National Research Council.

Mix, M.C., Farber, P & King, K.I. (1996). *Biology: The Network of Life,* 2d. ed. Glenview, IL: Harper Collins.

Montgomery, K. (2010). *Debating Glacial Theory, 1800-1870*. Minneapolis, MN: SHiPS Resource Center. URL: glacialtheory.net.

Nicherson, R.S. (1998). Confirmation bias: a ubiquitous phenomenon in many guises. *Rev. of General Psychology,* 2, 175-220.

Osborne, J. (2010). Arguing to learn in science: The role of collaborative, critical discourse. *Science*, 328, 463-466.

Panitz, T. (1996). Collaborative versus cooperative learning. URL: home.capecod.net/~tpanitz/tedsarticles/coopdefinition.htm. See also Washington, DC: ERIC Document #ED448443.

Postlethwait, J.H. & Hopson, J.L. (2003). *Explore Life*. Pacific Grove, CA: Brooks/Cole.

Savery, J.R. (2006). Overview of problem-based learning: Definitions and distinctions. *Interdisciplinary Journal of Problem-based Learning*, 1, 9-20.

Scharmann, LC., Smith, M.U., James, M.C. & Jensen, M. (2005). Explicit reflective nature of science instruction: evolution, intelligent design, and umbrellaology. *Journal of Science Teacher Education*, 16, 27–41.

Schommer, M. (1990). Effects of belief about the nature of knowledge on comprehension. *J. Educ. Psych.*, 82, 498-504.

Schwartz, R.S., Lederman, N.G.& Crawford, B.A. (2004). Views of nature of science in an authentic context: an explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Education*, 88, 610 –645.

Schwartz, T., Bunce, D.M., Silberman, R.G., Stanitski, C.L., Stratton, W.J. & Zipp, A.P. (1997). *Chemistry in Context*, 2d ed. Dubuque, IA: William C. Brown/American Chemical Society.

Seker, H. & Welsh, L. C. (2005). The comparison of explicit and implicit ways of using history of science for students understanding of the nature of science. Eighth International History, Philosophy, Sociology & Science Teaching Conference (IHPST), Leeds, UK.

Solomon, J., Duveen, J., Scot, L., & McCarthy, S. (1992). Teaching about the nature of science through history: action research in the classroom. *Journal of Research in*

Science Teaching, 29, 409-421.

Solomon, M. (2001). *Social Empiricism*. Cambridge, MA: MIT Press.

Tewksbury, B.J. (1999). Beyond hazards and disasters: Teaching students geoscience by probing the underlying influence of geology on human events. *Science & Education*, 8, 645-663.

White, H. (1992). Introduction to biochemistry: a different approach. *Biochemical Education*, 20, 22-23.

Wong, S.L. & Hodson, D., Kwan J. & Yung, B.H.Y. (2008). Turning crisis into opportunity: enhancing student-teachers' understanding of nature of science and scientific inquiry through a case study of the scientific research in Severe Acute Respiratory Syndrome. *International Journal of Science Education*, 30, 1417–1439.

Yaron, D., Karabinos, M., Lange, D., Greeno, J.G. & Leinhardt, G. (2010). The ChemCollective—virtual labs for introductory chemistry courses. *Science*, 328, 584-585.

Table 1. Key dimensions shaping learning environments and outcomes in case-based and problem-based learning.

- Case-based or decontextualized?
- Problem-based or narrative, or integrated?
- The focus is content, problem-solving skills, or context of science—or some combination?
- Problems apply knowledge or generate new knowledge?
- Case is historical or contemporary?
- Case is real or constructed?
- Solution(s) is open or closed?
- Problem is well defined, ill-defined or unspecified?
- Work is on paper, simulated on computer, or involves lab?
- Analysis adopts single perspective or multiple perspectives?
- Analysis is collaborative or individual?
- Scope of problem/scale of casework?
- Level/dimensions of student autonomy?