

Problem- and Case-Based Learning in Science: Distinctions, Virtues and Caveats

Douglas Allchin
[& others?]

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. Yet various characterizations of the process—sometimes profiled in direct contention with one another—can easily foster confusion about the features and virtues of this family of instructional styles. Here we forsake programmatic labels and taxonomies in the interest of clarifying some important distinctions or dimensions of the relevant teaching methods, while profiling their corresponding strengths and limits. How do such differences matter concretely to teachers and learners? Our primary focus is teaching science, although some of the instructional models and techniques have been pioneered in other disciplines and we imagine that our analysis may apply more broadly.

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 its cultural contexts also important? What about 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 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 inform teachers so that they may align desired aims with appropriate strategies or teaching tools.

Here, then, are comments on a series of significant distinctions (summarized in Table 1):

Case-based (Case study-learning) / Decontextualized

Most science textbooks present decontextualized, or abstracted, knowledge. Using cases, however, situates 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 (*situated cognition? -- Brown). 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 (citations), 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 (Gentner, Loewenstein & Thompson 2003; Kolodner, J.L., Hmelo, C.E. & Narayanan; Gentner & Colhoun 2008; +refs=?). 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.....

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 case-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 problems 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 and Singer 1996; Herreid 2005).

For more on the benefits [and limits] of problem-based learning generally, see Duch, Gron and Allen (2001), Hmelo-Silver (2004), Major and Palmer (2005). There is also substantial relevant 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, ref=?), 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 et al 2005, Seker & 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 [, ...? although at the current time, such examples are rare ?] (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 should appreciate the difference in cognitive processes: rationalizing a predetermined conclusion is different from justifying a new discovery — the former highly subject to error (through

confirmation bias).

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. They are all based on precedent, even if the cases invite creatively recombining extant ideas.) However, if the aim is for 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: the source of authority in knowledge (whether 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 completely 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 "science-made" 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 et al 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 echo existing perspectives.

Historical cases have their own virtues (Conant 1947; Hagen, Allchin and Singer 1996, v-vii; Allchin 1997, 2010). First, the benchmark content knowledge in standard curricula originated long ago. The strong pedagogical 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 "discovered" 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 et al 1992, Irwin 2000). 'Tentativeness of scientific knowledge', for example, has been a pervasive learning goal in science education for many decades (Lederman, Wade and 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. 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 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, not genuine.

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, 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. [refs?]

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*. One may also help foster skills in *posing problems*. 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" (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 et al 2010). Computers, in particular, offer unprecedented opportunities

through savings in computational time and access to vast data resources, unthinkable in education in earlier years. 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, due to different perspectives in solving 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; +refs?). When varying perspectives interact, one can enhance ways to analyze a problem or imagine its solution. Here, one may guide students in learning discursive 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 developing tolerance of 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 et al 2009; Allchin 2009a, 2009b; Montgomery 2010). 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 or collaborative. For more on the benefits and limits of collaborative learning in general, see <refs>.

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. 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 Global Climate Change Summit simulation 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. Fragments of information for solving a complex problem may well be artfully distributed among different roles, to help illustrate the potential value of collaboration.

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 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 (see biology text by Mix, Farber & King, 1996, 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*. 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 different levels of student autonomy, building increasing independence. Consider, for example, a series of challenges posed by Kugler (199-) 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. Dumping problems on students with little additional guidance will likely alienate students and sour the teacher-student relationship fundamental to continued learning. Equally problematic are projects where students breeze 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 similar 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 be mindful of different ways that autonomy may be exercised:

- selecting the problem

Student selection of the problem may contribute to the "buy-in" 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 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 activities 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 achievable 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.

Summary

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

In additon, 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 approach 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 continued partial 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 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.

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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?