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Systematizing Scaffolding for Problem-Based Learning: A View from Case-Based Reasoning

Andrew A. Tawfik (Northern Illinois University) and Janet L. Kolodner (The Concord Consortium)

Current theories and models of education often argue that instruction is best administered when knowledge is situated within a context. Problem-based learning (PBL) provides an approach to education that has particularly powerful affordances for learning disciplinary content and practices by solving authentic problems within a discipline. However, not all implementations of PBL have been equally successful at fostering such learning, and some argue that this form of instruction is beyond the capabilities of novices. We revisit the theoretical foundations of PBL and call on the theoretical foundations of case-based reasoning (CBR) to help us identify the reasons many PBL implementations do not succeed as well as expected. Based on that analysis, we suggest priorities for facilitator scaffolding during PBL, ways well-curated case libraries can expose novices to new experiences and help them direct attention to important variables that require additional investigation, and ways case-authoring tools can help foster the kinds of reflection needed for learning from problem-solving experiences. Finally, we discuss challenges that, if addressed, will support even more effective PBL implementations.

Keywords: case-based reasoning, case-authoring, case-based learning, case libraries, memory for experience, scaffolding, experiential learning

Introduction

Theorists argue that an important way to foster learner engagement and application of concepts is by having individuals solve authentic problems of a discipline (Ertmer & Koehler, 2014; Shaffer & Resnick, 1999). In particular, solving ill-structured problems, which have multiple possible solution paths that must be judged against each other, confronts learners with the need to make their goals clear, take multiple perspectives, and understand the nuances of the phenomena and processes needed to solve the problem. Such problem solving introduces learners to the kinds of problems that practitioners within the field encounter, while also providing a context for understanding how to apply the field's important concepts (Jonassen, 2011b).

Over the years, problem-based learning (PBL) has been shown to be a particularly efficacious instructional approach to supporting learners as they encounter disciplinary concepts and are introduced to domain practices (Barrows, 1980). This educational strategy originated within the medical field, but has since seen adoption in a variety of other domains (Herrington, Reeves, & Oliver, 2014; Hung, Jonassen, & Liu, 2008). When implemented well, students garner important problem-solving skills, such as information synthesis and causal reasoning, in addition to learning the content and practices of the field (Hmelo-Silver, 2013; Hung, 2011). As well, they tend to remember many of the problems they have solved and recall them later when they encounter similar cases, allowing them easy access to the previously learned concepts and skills (Hmelo-Silver, 2004; Spiro, Coulson, Feltovich, & Anderson, 1998). When implemented incompletely, however, the same results are not attained (Hung, 2011; Leary & Walker, 2009; Scott, 2014).

Our goal in this article is to explore some of the challenges to rigorous implementation of PBL and to suggest ways of overcoming those obstacles. A suitable lens for exploring and explaining the successes and failures of PBL, we believe, is case-based reasoning (Kolodner, 1993, 1997; Schank, 1999). Case-based reasoning (CBR) is a model of learning that focuses on the cognitive processes that lead to mental model building when learners are engaged in problem-solving and interpretation. Cases, according to CBR, are the interpreted versions of one's experiences. CBR further posits that as individuals gain experience, they have the opportunity to accumulate a rich and well-indexed case library in their own memories to reference as they encounter new situations.

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There are significant advantages for learning such as memory building and recall; and we claim that PBL could be an even more powerful instructional approach if it were implemented in ways that explicitly target the construction of a rich mental library of easily accessible cases.

In this paper we first revisit the principles and benefits of PBL, the circumstances in which those benefits accrue, and some of the challenges to effective PBL implementation. We then discuss the lessons CBR teaches about helping learners build rich and easily accessible mental libraries of cases. Those lessons, we will claim, can be applied to alleviate many of the challenges faced during a PBL implementation. In particular, we suggest priorities for facilitator scaffolding during PBL, ways well-curated case libraries can expose novices to new experiences and help them direct their attention to important variables that require additional investigation, and ways case-authoring tools can help foster the kinds of reflection needed for learning from problem-solving experience. We argue, as well, that both types of software can share scaffolding responsibilities with the facilitator, making the facilitator's job easier to carry out, and that availability of such case libraries can make it easier to systematize and share curriculum. Using cases in this way may also help with the scalability and standardization of a PBL implementation.

PBL and Its Guiding Principles

PBL was designed as a systematic and highly sequenced approach to simultaneously learning the knowledge of a domain and the skills and practices of a discipline through problem-solving activities. In its original formulation, a medical problem (often called a *case*) is presented to students (Barrows, 1980). Students work together to generate hypotheses about the diagnosis, identify gaps in understanding, generate questions they need to answer to fill those gaps (called *learning issues*), keep track of what they are learning, and generate viable solutions. They record their deliberations on a specially formatted whiteboard with columns for recording knowledge, ideas, and learning issues. After working together to consider the case using their existing knowledge, students collectively identify resources they think they will use in their investigations, discuss how to use them well, and then separate and investigate the issues, each giving extra attention to some set of assigned issues they confront.

When students congregate again, they discuss the resources they used and how they used them. They then return to their problem-solving activity, offering their revised understandings of the case given insights they gained during their investigations. In turn, they reconsider their hypotheses while identifying any new issues they need to investigate to solve the problem. This cycle continues until students (or the coach/facilitator) are satisfied that they have solved the problem. Learners deepen their collective understanding of disciplinary phenomena and processes in the context of collaboratively moving forward in solving the case. They are then presented with the expert opinion on the case. If different than their conclusion, they try to determine why their solution was different, affording additional opportunities to refine the content they are learning and their ability to carry out reasoning in the discipline.

Throughout the deliberations, coaches (called "tutors" in the original formulation) guide inquiry and sensemaking (Barrows, 1980). When problem solving is complete, coaches help learners reflect on their experiences by asking them to articulate the concepts and skills learned as well as their contribution to the group's collective problem solving. This reflection is especially important for helping learners identify the skills and practices needed for problem solving, the full range of skills needed for collaboration and articulation, and the principles behind those skills (Belland, 2014; Hmelo-Silver & Barrows, 2006).

This sequencing of PBL activities is designed as an integrated whole. Together, activities help learners identify what they know and recognize when they need to learn more. The sequencing is also aimed at helping learners identify and articulate the important concepts they are learning and the skills that are important to their collaborative problem solving. Over time, learners have the opportunity to revisit the concepts and skills they are learning as they reuse them to solve new problems. Reflection across cases helps learners gradually develop their capabilities and iteratively refine their understanding of key disciplinary phenomena and processes.

PBL thus moves educational practice away from the tradition of teachers telling and students answering questions with right and wrong answers toward an educational approach that focuses on solving complex problems together and, in that context, learning the content of a domain. Such activity, research shows, holds the potential to engender critical thinking, collaboration, and communication skills germane to a field (Hung et al., 2008; Savery, 2006). The method was first used in the medical field (Barrows, 1980) and has since seen adoption in fields such as pre-service teacher education (Glazewski, Shuster, Brush, & Ellis, 2014; Hmelo-Silver, Derry, Bitterman, & Hatrak, 2009), business education (Tawfik & Jonassen, 2013), engineering education (Bédard, Lison, Dalle, Côté, & Boutin, 2012; Mitchell & Smith, 2008), and STEM K–12 education (Asghar, Ellington, Rice, Johnson, & Prime, 2012; Brown, Lawless, & Boyer, 2013; Kolodner et al., 2003).

Challenges to the Effectiveness of PBL

A complete and authentic implementation of PBL includes all of the cycling, coaching, and taking on of roles discussed above. Research shows that when implementations include all of these pieces, individuals learn disciplinary content as well as or more deeply than those who are educated in more traditional ways (Hmelo-Silver, Duncan, & Chinn, 2007). Students also learn practices of the discipline, come to appreciate the roles others can play in helping them do their job well, and gain collaboration and communication skills (Herrington et al., 2014; Hmelo-Silver, 2004; Schmidt, Loyens, van Gog, & Paas, 2007).

However, in different disciplines, at different institutions, at different education levels, and across different teachers or coaches, there is a great deal of variability in the ways PBL is implemented (Azer, McLean, Onishi, Tagawa, & Scherpbier, 2013; Hung, 2011). The original PBL had a coach for every seven or eight medical students, and cases were used to cover the entire first two years of the medical school curriculum (Barrows, 1980). To support the need for doctors to appreciate the nuances and variations of expert reasoning, students encountered up to 200 cases during their first two years of medical school—some officially in the curriculum and some encountered in clinic and discussed afterwards (Williams, 1992). But as PBL has been taken on by different disciplines and institutions, it has lost some of that scope, and along with it, its powerful potential for affecting learning. In some situations, for example, instead of a complete problem-based curriculum, practice cases may be presented to students after instruction to give students the experience of applying what they are learning (Dabbagh & Dass, 2013); in this situation, most time is given to problem solving and little to sensemaking. As well, in this situation, students may encounter only two or three cases in a semester (Jonassen, 2011b). When opportunities for collaborative sensemaking are foreshortened, so are opportunities for deep and nuanced learning of disciplinary content (Kapur, 2014). And even when problem-solving activity makes up the bulk of activity in some disciplinary class, students still encounter only a few cases in a year because they are solving problems in one class of the many they are taking. As well, in middle school and high school settings, PBL is generally implemented in classrooms with one teacher and up to 30 students. It is thus harder for teachers to tailor their advice to the needs of individuals and harder, still, for a class of 30 to have the kinds of reflective sensemaking discussions that are so important to learning from problem-solving experiences. Under all of these circumstances, the cycle of revisiting what has been learned across cases is limited, making it harder to consistently foster both deep learning of content and learning of domain practices (Anderson, 1982; Jacobson & Spiro, 1995; Kolodner et al., 2003).

As well, teachers, facilitators, and those developing PBL curriculum units are not always well-educated in the foundations of PBL; while they know many of the basics, they may not understand the reasons why the pieces are integrated into the whole of the cycle. The result is that many implementers de-emphasize or skip the reflection pieces of the cycle because it takes so much time (Hmelo-Silver & Barrows, 2008). In other implementations of PBL, so much time is spent on a first attempt toward a solution that there is not time for the iterative cycling that PBL calls for (Dolmans, De Grave, Wolfhagen, & Van Der Vleuten, 2005; Hmelo, Holton, & Kolodner, 2000; Hong & Choi, 2011). And in other situations, the facilitator fails to provide students the scaffolding they need along the way to focus their activity and to express themselves in rigorous ways. When the integrity of the PBL approach is compromised (e.g., the number of cases learners address is small, the iterative cycling is foreshortened, or reflection or scaffolding are de-emphasized), the approach cannot be expected to produce the powerful results of a full implementation (Hung, 2011).

It is easy, therefore, for critics to question the true impact of PBL (Kirschner, Sweller, & Clark, 2006). If implementers do not facilitate well, then solving complex problems is too difficult for learners, and if reflection is not facilitated well or is de-emphasized, learners will not all be able to systematically draw lessons from their problem-solving activities. Further, if learners do not experience enough variety of cases, there is little chance they will develop the cognitive flexibility afforded by a PBL curriculum (Jacobson & Spiro, 1995). Indeed, a variety of meta-analyses have underscored the variability in PBL results as they relate to discipline, problem-type, and developmental phase (Leary, Walker, Shelton, & Fitt, 2015; Walker, Leary, & Lefler, 2015).

Revisiting PBL's Foundations From a Case-Based Reasoning Perspective

We claim above that the lessons CBR teaches about helping learners build rich, accessible mental libraries of cases could alleviate many of the challenges of making PBL more systematically effective. CBR provides a model of the cognitive processing necessary to reason and learn from one's experiences (Kolodner, 2002; Schank, 1999) that aligns with the goals of PBL. Consistent with much other literature in cognitive science and the learning sciences (Anderson, 1982; Bransford, Brophy, & Williams, 2000; Tulving & Thomson, 1973), CBR supports the theoretical foundations for Barrows' (1980) original formulations of PBL sequencing and tutors' responsibilities. CBR also makes suggestions about how to focus scaffolding for the ability to reuse what one has learned and ways that technology might lighten the load of modern-day facilitators, and still foster the kinds of deep understanding that are possible using PBL. We begin with the theory and implications for scaffolding and then discuss the roles technology might play in addressing PBL's implementation challenges. We then address the questions that still need to be answered to use CBR technology to its fullest.

CBR (Kolodner, 1993; Schank, 1999) refers to reasoning based on previous experiences, also known as *cases*.[1] Facilitators can support remembering a previous experience (or case) in order to provide insights that prompt the reasoner to solve the new problem. This can be done by adapting an old solution to the new situation or merging pieces of several old solutions. By reinterpreting a new situation through a recalled case, a reasoner can identify potential solutions. Recalling a case and comparing it to a solution in progress also allows the reasoner to identify the solutions' potential effects. As learners reason based on their experiences (cases in memory), they develop general and abstract knowledge through comparing and contrasting similar cases to each other.

Access to one's knowledge, it follows, is mediated by the interpretations of our experiences and the ways we distinguish them from one another during initial and later encodings.[2] When a new problem is encountered, memory identifies the most similar knowledge sources it has available that can help in its interpretation. A knowledge source may be a particular interpreted and concrete previous experience, or it may be a generalization created based on similarities across experiences, or it may take some abstract form. Regardless, a knowledge source is accessed through a retrieval process that sorts through cases and their associated generalizations in order to find what memory is most applicable to the new situation.

CBR identifies two sets of procedures that allow such recognition to happen: one set runs at insertion time, and the other set runs at retrieval time. While having experiences, reasoners interpret what they are experiencing—noticing what happens, reasoning about and often identifying why things are happening, working toward solving problems that arise, and generally making sense of a situation. The interpreted experience is inserted into memory as a case. When the reasoner, in addition, identifies at least some of the lessons that experience can offer when solving future problems and when those lessons might most productively be applied, then the case can be labeled (indexed or tagged) in ways that allow it to be recalled when it will be useful in later reasoning. The case itself includes what happened, explanations derived while solving its problems, lessons the reasoner thinks the experience could offer, labels for later access using characteristics that differentiate it from other similar cases, and what the reasoner thinks are the conditions under which its suggestions might be usefully applied in the future.[3] The most discriminating labels of a case will be derived by a reasoner who has the background knowledge to carefully analyze a case's potential applicability and distinguish its applicability from that of other cases.

At retrieval time, a reasoner uses his or her current goals and understanding of the new situation that is being experienced as a probe into memory. The memory probe includes all of the known and derived characteristics of the new situation—interpretations of what happened, connections, explanations, and so forth. Particular emphasis is put on what the reasoner can figure out about (1) the characteristics of the new situation that are most important to focus on in further interpreting the situation or solving the proposed problem and (2) the ways it is different from other similar situations the reasoner has encountered. The reasoner uses this probe to access previous cases that may be usefully similar to the new one, and therefore potentially applicable in solving the new problem. The extent to which a reasoner is willing or able to interpret the new situation to identify what seems most important about it determines the quality of the probe into memory. The more systematic and careful a reasoner is at interpreting a situation and identifying its most relevant characteristics, the more likely s/he is to find relevant knowledge and experience to use in reasoning. When the work of identifying the new situation's most important characteristics has not been done, or when the reasoner does not know enough to do that, the resulting memory probe will result in poorer access to the contents of memory than if the probe is more embellished.

According to the CBR model, after retrieving a relevant case from memory, a reasoner judges its applicability and if s/he finds it applicable, s/he applies its lessons to the new situation or copies and adapts its solution for the new situation. After this works several times, the reasoner can be relatively sure the lessons of the retrieved case hold up and might extract a generalization; however, the reasoner may find that s/he does not know how to apply what a previous case suggests or may apply something learned in an old situation and have it fail. Both situations suggest a need to revise what is known and/or the way the retrieved case is labeled in memory. The reasoner then attempts to derive an explanation for the failure that encompasses both the old and new experience. During this process, the reasoner may revise the interpretation of any retrieved case or even relabel their immediate interpretation of the new experience.

CBR thus gives failure and iterative refinement central roles in promoting learning and facilitation. When an outcome or solution is unsuccessful, the reasoner is alerted to a deficiency in his or her knowledge. When such failures happen in the context of attempting to achieve a personally

1 Note that CBR refers to interpreted experiences as *cases*, while *cases* in PBL are problems to be solved.

2 It follows that when many experiences are so similar to each other that there is little to distinguish them, the specifics of each become inaccessible.

3 The CBR literature calls this *indexing*; we use the terms *labeling* and *tagging*, as these are the more contemporary terms for essentially the same thing.

meaningful goal, a reasoner wants to engage in inquiry and explanation to overcome the failure. A reasoner who knows why s/he reasoned the way s/he did will be able to identify what poor understanding was responsible for a reasoning failure and which understandings need to be refined. It is therefore key for PBL facilitators to identify these issues as learners engage in inquiry. If, in addition, a reasoner gets feedback about what results from the initially attempted solution, s/he will be able to label her or his experiences in ways that discriminate their usability and allow good judgments for later reuse. Facilitation of such iterative refinement is possible only when iterative cycles of problem solving (making solutions better over time) are built into the sequencing of activities and when learners have the opportunity to address follow-up problems that require use of what they learned previously.

It follows that learning, from the point of view of CBR, takes three major forms: (1) extending one's knowledge by interpreting and labeling new experiences and incorporating them into memory, (2) reinterpreting and relabeling old experiences to make them more usable and accessible, and (3) abstracting out generalizations over a set of experiences. From a learning and facilitation aspect, the most useful interpretations of an experience include an explanation that connects one's goals and actions with resulting outcomes (e.g., the additional oregano in the tomato sauce was responsible for its enhanced flavor; the movement in the hallway distracted workers in windowed offices keeping them from getting their work done). CBR thus points out the importance of PBL's final reflection activities: making experts' analysis of cases available to learners, and making time for identifying what learners did well and why their solutions were different from those of experts. According to CBR, learning from experience depends heavily on the reasoner's ability to create such explanations, suggesting that the motivation, opportunity, and ability to explain are key to promoting learning. The need for such explanations justifies the communal sensemaking and explanation that are foundational to PBL.

Addressing PBL Challenges Using CBR: Some Proposals

Case-based reasoning makes a variety of suggestions about overcoming obstacles to comprehensive PBL implementation, and almost all of them stem from its focus on the central role of interpreted experience in learning and reasoning.

CBR's first set of suggestions are about the reflection that is essential to learn from experience and how to scaffold that reflection well (Kolodner, Hmelo-Silver, & Narayanan, 1996). The more a reasoner has explicitly noticed and made sense of what is going on in a situation, the richer its case representation will be; this suggests that during problem solving, facilitators should help learners make explicit the reasoning they are doing, the knowledge they are using, the connections they are making, and justifications for the decisions they made. The more effort a reasoner has put into identifying what can be learned from an experience and when those lessons might usefully pertain, the better the learner will be able to label the experiences and apply them for future use. This suggests that reflection after problem solving should aim to extract lessons learned from the problem-solving experience and anticipate the conditions when those lessons could be useful. Facilitators play a crucial role in helping learners maximize the value of this reflection.

Failures encountered by learners during problem-solving, in particular, is a powerful indicator of a need to learn more or refine one's understanding. This means learners need to have opportunities to recognize when their problem solving could have been done better. One way to support this in PBL is by having learners look at the way experts would have solved a problem and compare what they did to the reasoning of experts. The facilitator's role in these situations is to help learners—both individual learners and the collective—notice failures in reasoning, identify deficiencies in their knowledge or reasoning that led to each failure, move toward fixing those deficiencies, and identify ways of labeling the experience so that they can remember it later to avoid making the same mistake again.

CBR's second set of suggestions is about helping learners as they solve problems. CBR tells us that using what one learned from a previous experience in a new situation and experiencing failure is essential to nuancing one's understanding of a case. An important facilitator role, therefore, is helping learners recognize the previous experiences they have had that might serve as useful suggestions for solving the new problem. If learners explicitly reuse their old experiences, they will have better opportunities to recognize distinctions they need to be careful about in the future. Indeed, the need for making subtle distinctions justifies some of the seeming redundancies in the PBL cycle; leaving out opportunities for reflection, CBR and other literature tell us (Jonassen, 2011a), necessarily means that experiences will be less well integrated into memory (their contents and labels will be less nuanced), and what is learned from them will be less deep and refined.

But CBR's justifications of PBL's approach present a formidable dilemma under circumstances of use outside of a full PBL-driven curriculum: Maximizing the benefits of PBL requires all the sequencing in the PBL cycle, masterful facilitation, and work on a large variety of problems/cases. These are exactly the issues that make PBL difficult to implement well, and when we recall that novice learners have a hard time solving problems due to limited prior knowledge, it may seem that the denigrators of PBL have a point.

CBR's other set of suggestions addresses these issues, specifically its suggestions about the roles technology might play. First, CBR suggests using well-curated case libraries as resources that allow learners to vicariously experience a more representative set of cases in a domain. Second, CBR suggests using case-authoring tools to help scaffold reflection, sensemaking, and labeling. Adding such learning technologies into PBL's systematic approach, we claim, can lighten the load on facilitators and help them be better scaffolders. In this way, learners glean more from activities as they make connections with the lessons described in the cases. In doing so, the rigor and depth of whole-group discussions are improved. Use of such technology might also decrease the time needed to address each case, and a well-curated case library could provide a step toward standardizing PBL curriculum across organizations.

Well-Curated Case Libraries as Resources

In PBL, learners are often asked to solve one case for a given time period, which potentially limits the case exposure during a PBL curriculum. A *case library* is a repository (database) of the interpreted experiences of others that inform a solution to the main problem to solve (Kolodner, Dorn, Owensby, & Guzdial, 2012; Kolodner, Owensby, & Guzdial, 2004). Its cases can come from a variety of places, including the literature, experts, and peers. This may support scalability of PBL because each story teaches a lesson and includes what is needed for the learner to understand the lesson and how to apply it. A case can have many stories associated with it or just one. A useful medical case, for example, may tell the story of how a particular disorder presented itself or progressed, or it might include a story about diagnosing a patient with a confusing set of symptoms, or it may include both stories if both are interesting and have useful lessons to teach. An engineering design case might present stories about how several different design decisions were made. Valuable stories include those that help a learner understand a situation, the solution that was derived, and why it was derived that way, or what happened as a result. The *New York Times* publishes such cases regularly in its Well column, as do publications such as the *International Journal of Designs for Learning* and *The ID CaseBook*: *Case Studies in Instructional Design* (2013).

Learners can use case libraries in many ways as they are solving new problems. A learner might begin his or her problem solving by entering descriptors of the problem s/he is working on and asking to see cases with similar characteristics. This would provide the learner with the "lay of the land," suggesting the variety of solutions or issues s/he might consider in solving the problem. The learner might also be working on a particular issue and ask the case library to retrieve similar cases where that issue arose. Or, the learner may identify something s/he thinks s/he learned and ask the case library to retrieve cases with that pattern in them. Alternatively, when contemplating a solution, the learner may use the case library to know the results when that solution was used to solve a previous problem. Because cases in the case library are labeled both by their characteristics and based on the stories told about them, learners have opportunities to mix and match the set of cases they examine at any time based on their goals and ideas at that time. Sets of cases that are immediately available to a learner when s/he is grappling with some issue can help the learner identify solutions, predict outcomes, or identify issues to address.

The scope of a case's applicability depends on the case's quality, while the benefit of a case library depends on the range of cases it contains. CBR provides the following advice about designing effective case libraries (Kolodner et al., 2012; Owensby & Kolodner, 2004):

- *The case library that is made available to learners should include cases that show the applicability of key concepts, skills, and show many of the variations in the way each is understood and/or applied.* Research indicates that it takes several encounters with a concept or skill to learn it well (Jacobson & Spiro, 1995; Redmond, 1990); encounters that cover the range of applicability of the concept or skill allow the learner to see its varied uses, the other concepts or skills it is related to, debug its applicability, and refine its definition. There is not time in school for students to actively experience the full range of applicability of any concept, but sharing the experiences of other learners and looking at the ways experts have applied concepts and skills can fill those gaps. For example, in a middle school science unit on geology (Owensby & Kolodner, 2004), learners are challenged to plan the underground route of a transportation tunnel while taking into account the geology of the region. They examine related cases about difficult-to-construct tunnels and mines that help them understand the geological issues they need to consider when making their recommendations and possible solutions to key challenges in tunnel design and construction. Cases in Dorn's (2011) ScriptABLE system helps new programmers anticipate problems they might encounter as they are doing web design—the conditions under which those problems might occur, how to track down each problem, and how to address each.
- *A case can be composed of one or many stories; full details of every case are not needed, but rather, enough is needed to make sense of and be able to apply what can be learned from the case.* It would be too hard to populate a case library if every case in the library needed

to have complete information; instead, it is sufficient to identify stories that make important points and to make cases around those stories. A story might help a learner identify what to focus on in understanding a new problem or how to make sense of something they are experiencing or observing. In addition to a solution, the narrative might identify important steps toward finding a solution, mistakes that are often made, what to watch out for in some circumstance, or outcomes if a problem is solved a certain way. Each case needs to include enough detail so that its stories can be understood and applied well. Schank's ASK systems (Schank, 1999; see more below) focus on the stories in cases, giving learners access to potentially useful stories (rather than full cases) at times of need. For example, in an ASK system used to depict how to start a business (Dickson-Deane, Henry, Graber, & Tawfik, 2010), a learner can read a narrative about how an aspiring entrepreneur wasted resources hiring new employees over and over again rather than figuring out how to use the employees he had available when his company was new. That left him with little in the way of financial resources needed to build a business.

- *In deciding which details need to be included in cases, think about the difficulties learners will have while solving problems, the reasons a learner might access a case and what it might help them with, and include what is needed for those purposes (Kolodner, 1993).* Deciding if a retrieved story is applicable to a new situation is easier if the learner has access to the justifications or explanations behind what happened in the old situation. The better the justifications for decisions reported in stories, the more easily a learner will be able to determine if s/he might make a similar decision. Furthermore, the better explanations of why something happened the way it did, the more chance that a learners will be able to predict what might happen in the new situation. When a case includes not only what happened, but also the resources and reasoning used to understand a situation, make choices, or solve a problem, cases can serve as a more knowledgeable peer for both learners and teachers, helping learners interpret situations and solve problems and also providing a model of good scaffolding for the teacher.
- *Organizing labels into an indexing system and making that indexing system available to learners can scaffold problem solving and learning.* When case labeling is systematic, the labels used to tag cases can be codified in an indexing system. A case library's indexing system, if it is available for examination, can serve as an advanced organizer for a learner or even can scaffold how the student thinks about his or her own experiences (Feltovich, Spiro, Coulson, & Feltovich, 1996). For example, the system of indexes in a case library called Archie-2 (Domeshek & Kolodner, 1993) helped architecture students understand the issues that need to be addressed in public library design. They used a menu to develop a description of the kind of case or story they were looking for in the case library. The available entries in the menu suggested issues, spaces, and perspectives they might consider as they moved forward with their designs. While the cases provided advice about how to address each of those issues, the case library's indexing system provided a view of the domain's major concepts, their relationships, and guidance on what to focus on when designing or solving problems.
- *When a case library will be used to support some particular type of problem solving that is repeated over and over, a useful way to provide access to cases is through questions that learners will wonder about as they are solving problems. ASK system*s (Ferguson, Bareiss, Birnbaum, & Osgood, 1992; Jonassen, 2011a) anticipate questions that learners might need answers to as they are solving problems and embed the questions themselves as links to cases in the system. One such ASK system was designed to teach aspiring entrepreneurs about how to start their business (Dickson-Deane et al., 2010). Within each topic (e.g., "How do I begin marketing my product?"), learners are presented with a set of related questions (e.g., "What should my budget be for marketing?"; "Where are the best places to advertise?"; "How big should my marketing staff be when I am just starting out?"). When students click on the link, they are taken to a narrative that describes how practitioners have encountered this particular problem in practice. Learners can access the stories just in time to address emergent challenges as they encounter them during their problem solving. Such systems can be implemented as stand-alone resources that integrate with a curriculum, or can be embedded into the courseware learners are using (e.g., an immersive environment, a case handbook, or a textbook).
- *Stories that describe somebody's problem-solving or design process can show how others have defined problems and proceeded through to a solution.* Arguably, the most challenging task for novices in a discipline or domain is how to initially define the problem properly (Schon, 1984). Stories that show or tell how somebody else went about addressing a similar problem can provide help with getting started. The Stable program (Guzdial & Kehoe, 1998), for example, provides

support for getting started and keeping on track. In this system, cases are the excerpts from programs others have written that achieve some necessary function; the stories in each case are about why the programmer decided to implement pieces of the excerpt in particular ways.

- *Using the experiences of others to solve new problems is a complex but essential metacognitive activity, and scaffolding associated with case libraries can be used to help with development of such skills when cases highlight the reasoning others used to solve similar problems.* In one example, a tool called CAS (Case-Application Suite; Owensby & Kolodner, 2004; Kolodner et al., 2004) was successfully used in middle school science classes to help students reason about what they needed to learn about the geology of a location where they were considering placing a tunnel and how it might be built. Its cases, all describing real tunneling dilemmas and disasters around the world, included stories about how experts had solved problems they were addressing, why they made the choices they did, and what happened as a result. CAS used relevant cases and stories to guide students in extracting and applying the important material from the stories' content through questions and examples that narrowed their focus while reading. This method not only helped students solve their tunelling challenge but also structured and strengthened their case-based reasoning capabilities for future problem solving (Owensby & Kolodner, 2004).

There are multiple ways in which cases may be presented to the learner. For instance, Archie-2 presents its stories using a combination of text, photos, and schematics—the kinds of representations architects work with. Stable (Guzdial & Kehoe, 1998) and Dorn's (2011) ScriptABLE, which was designed to help software developers, show their cases as programs with textual annotations attached. ASK systems often depict experts telling their stories in the form of videos or text . What is important is that stories in a case library should be told in ways that are consistent with what the community of users expects (e.g., annotated architectural plans for architects) and in ways that that hold learners' interest. The cases are aimed at the developmental and knowledge levels of targeted learners, use domain knowledge to justify decisions and/or explain effects, and provide pointers to other resources that can deepen his/her understanding. Also important is that cases and stories be labeled for accessibility in ways that are consistent with the ways learners think about the problems they are solving. Doing so requires anticipating the expected knowledge level of targeted learners and the circumstances under which they might find each case and story helpful. Moreover, each case and story should be composed and labeled so that learners with many different understandings of a domain will be able to find and understand them.

Case-Authoring Tools

A case-authoring tool is a resource that helps learners author cases based on their own experiences. The need to write up one's experiences for others to read requires sufficient review of the experience to be able to summarize its most salient parts. When authoring a case for others to utilize, learners must become adept at articulating their interpretation of their experiences—telling what they learned from their experience in a manner others can understand and identify—as well as identify appropriate ways of labeling their experience for easy access. Authoring a case thus requires reflecting on a situation, sorting out its complexities, making connections between its parts, and organizing what one has to say into coherent and memorable chunks—exactly the kinds of interpretations of experience that CBR tells us are important to productive learning from experience. CBR suggests that the more attention is put into each of these interpretation tasks, the more productive learning will be. Case-authoring can also be a particularly motivating way of encouraging effective reflection if learners know that the cases they authored will be valuable to someone else at a later time (Scardamalia & Bereiter, 1994).

A good case-authoring tool encourages learners to reflect on issues they had to address in solving a problem; the achieved skills during a design challenge; the kinds of solutions they constructed; and what happened as a result of those solutions. If the solution did not work as well as expected, learners can also reflect on lessons that can be learned from the situation and the kinds of future situations in which those lessons might be useful. Case-authoring tools can provide more or less structure to learners as they write up their experiences. Reflective Learner (Turns, Newstetter, Allen, & Mistree, 1997) helped undergraduate students in project-based design courses write "learning essays" about their design experiences, providing each a way of keeping a personal portfolio of what s/he had learned. Reflective Learner simply prompted students to articulate their goals, how they went about achieving them, what was difficult, and what could be learned from their experience. Despite the simplicity of its prompts, analysis showed that students who used Reflective Learner wrote longer, more structured essays and received significantly higher grades than those who did not (Turns et al, 1997).

Providing more structure makes it easier for younger learners to author cases that others will find useful. SMILE (Kolodner et al., 2012, 2004; Kolodner & Nagel, 1999), for example, is designed as a suite of tools for middle schoolers, each prompting for a specific kind of experience students have during project-based inquiry activities in science class. In this system, two tools prompt for writing up experiences about designing and running an experiment, another prompts for writing up experiences designing a solution to the project challenge, another prompts for writing up experiences trying out a solution in progress, and so on. Though each has different prompts, each is asking students to reflect on their goals, solutions, how well those solutions worked, what they learned, and when what they learned might be useful. Similarly, STABLE (Guzdial & Kehoe, 1998) provides structuring and prompts specific thinking about one's programming experiences.

In addition to providing help for writing up their experiences so others can learn from them, a good case-authoring tool also provides help in choosing labels for cases. In SMILE, learners are asked to label their cases in a way that describe the situation, describe their goals, describe the confusing thing(s) that led them astray, and so forth. Having learners author and label cases based on their experience has two practical benefits. First, for the learner it fosters the kind of reflection that will identify lessons learned so as to reuse this knowledge in future problem solving. Second, the activity also generates a case library that can be referenced by other learners to benefit from the recorded experience.

Which such cases and the percentage of such cases belong in a curated case library are questions we still do not know the answer to. We do know, however, that learners will engage in such case-authoring only if they are mature enough to recognize how useful the required reflection will be to their learning or if they know that the cases they author will be useful to others. It is hard, for example, to get middle schoolers to write up their experiences. But in Learning by Design (Kolodner et al., 2003) middle school science learners are willing to use SMILE to author cases because the curriculum is structured to encourage collaboration. Distributing investigations across small groups in class necessitates students share each other's results and ideas to complete challenges. In Kitchen Science Investigators (Clegg & Kolodner, 2007; Gardner & Kolodner, 2007), Kitchen Chemistry (Clegg et al., 2012, 2014), and Sci-dentity (Ahn et al., 2014), middle schoolers are willing to write up their experiences because of the personal relevance they have found in the activities they have engaged in and their pride in their accomplishments. That makes them excited about sharing their recipes, what they've learned about cooking, and their science fiction stories with their peers, families, and neighbors. Sheridan (2015) also designed a case-authoring tool for participants in maker spaces, mostly for middle schoolers and high schoolers. They report that participants seem willing to write to explain their process for adults and to keep track of where they are making progress (Sheridan et al., 2014).

Undergraduate engineering students are more willing to engage in the writing up of experiences that engender reflective learning. For example, participants in the Design for America program (Gerber, 2014; Gerber & Easterday, 2015; Gerber, Olson, & Komarek, 2012) use the Digital Loft (Easterday, Lewis, & Gerber, 2013) to scaffold real-world design projects. This software provides scaffolding in the forms of structuring and hints using cases and stories of other engineering design teams. Loft participants perceive examples of other teams' work as a valuable and desirable way to learn new methods, and they enjoy writing up their design experiences as cases and stories for others for various reasons. First, learners receive valuable feedback from their peers about how to improve their work and what to do next. Second, learners feel they are making contributions to a community of student engineers who are trying to do good in the world.

Remaining Questions

Designing Case Libraries and Case-Authoring Tools

There is much literature about how to design case libraries and case-authoring tools. However, designing and building those tools so that they work well for particular learners or in particular disciplines is not so easily accomplished. Therefore, the particulars of what is needed in different disciplines and at different developmental stages needs to be identified for specializing each case library and case-authoring tool to its targeted learners. As well, too little is known about the nuances of designing these resources and tools so that the scaffolding provided by teachers and technology complement each other well. For example, how can we help learners identify which of several cases they find in a case library might be useful? As well, we know that there are learning benefits in comparing and contrasting cases to each other (Bransford & Schwartz, 1999; Gentner & Colhoun, 2010; Gentner, Loewenstein, & Thompson, 2003; Lin-Siegler, Shaenfield, & Elder, 2015)—both across contexts and within contexts, both for purposes of sensemaking and of achieving problem-solving and design goals—but more needs to be known about how to help learners recognize that comparing cases might be useful and how to help them carry out a comparison and learn from it.

An issue we need to learn more about is the extent to which learners are able to appreciate the nuances in the cases of experts and what that means about when it is worthwhile for learners to read the cases of experts. It is also important to understand what circumstances it makes sense for learners to revisit expert cases and the scaffolding needed to learn from them. This will differ from discipline to discipline and between developmental levels of learners. The original formulation of PBL had learners access the cases of experts only after they tried to solve a problem themselves; it was thought that they would not be able to appreciate the complexities without that experience and that it would be difficult early on for learners to know how to make sense of those cases. And it was not assumed that visiting an expert's case once was sufficient for learning; learners were often challenged to solve some problems twice—once early on to introduce them to the issues of a field, and once later to help them bring together what they had learned and allow them to experience their deepening understanding. They revisited the expert's reasoning on that same case twice as well—once early and once later, presumably with the ability the second time to glean more of its nuance.

With case libraries and case authoring tools available to learners, much more of this revisiting is possible; learners can access not only the expert solutions to problems they are solving, but also (1) the expert solutions to other similar problems, (2) the novice solutions to those same problems, and (3) their own recorded experiences addressing similar problems. Each encounter holds different affordances for fostering learning, dependent on what the learner already knows, what the learner is seeking to learn, and the lessons the case itself has to offer. Each encounter also affords reinterpretation of the lessons of a case and modification of its labels. We know the potential power of the kind of incremental building of understanding afforded by such revisiting; we don't know, however, if there are patterns of revisiting that are more productive than others or how the impacts of revisiting one's own experiences, those of peers, and those of experts differ.

There are a variety of other issues that require further research. Specifically, other issues need to be addressed for specialization of case-authoring tools to different disciplines and learner populations. What kinds of stories do we expect learners to be telling in their cases, and what help do they need telling those kinds of stories? What kinds of stories are they failing to tell that would foster better learning from their experiences? What kind of help do they need to recognize those stories and tell them well? Which reflection is most important for extracting out content understanding from their experiences? Which reflection is most important for aiding mastery of skills and practices of a discipline? How should that reflection be distributed over the many problems they are solving? How much case-authoring should we require of learners? They will lose interest if they are forced to write too much; on the other hand, if they are only solving a small number of problems, they do need to get the most out of each. These design issues will impact the degree to which cases are recalled and later reused.

Populating Case Libraries With the Right Sets of Cases

A whole variety of issues arise when thinking about how to make sure the right cases are included in a case library. What does it mean to have an appropriately representative set of cases available for learners in a discipline? One issue with respect to answering this question is the relative value of learning from one's own experiences versus those of others. One's own experiences are richer than those of others with respect to detail but weaker in terms of connections and explanation. The experiences of experts are richer in connections and explanations but have fewer details and may go beyond what a novice can understand. The experiences of other novices include descriptions of mistakes made during diagnosis and treatment. Each has its uses, and we need to learn more about how learners make use of each to populate case libraries well.

Also important to consider is the relative importance of encounters with success and failure stories from a case library. In one study, for example, Tawfik and Jonassen (2013) found that learners with access to only failure cases outperformed those who encountered only success cases on measurements of counterargument and overall holistic argumentation scores for college-level business students. We do not know if there is some particular mix of success and failure cases a case library should have, though we do know that those developing case libraries for novices should begin by identifying the difficulties novices have and the variations in ways of accomplishing things in the domain that novices need to be aware of.

Conclusions

PBL and other problem-solving approaches to education have seen increased adoption across many different educational contexts. However, the way in which these approaches have been implemented has seen a considerable amount of variability (Leary & Walker, 2009), which has led to criticisms of the instructional strategy. Some have gone so far as to question whether the method of instruction extends beyond novices' cognitive load (Schmidt et al., 2007), suggesting that a problem-solving approach to education should be abandoned.

But there is significant evidence that, when done well, PBL and other problem-solving approaches to education have powerful affordances for better preparing disciplinary expertise. Addressing the challenges to making such education effective, we believe, requires both making better use of what is known about how people learn from experience and learning more about how people learn from experience. CBR provides recommendations for how to leverage the experiences of others as scaffolds when novices lack experience and how to encourage the reflection on experience needed to foster learning from problem-solving experiences. It also suggests further research needed to understand how to integrate digital tools that will make it easier to manage a PBL curriculum approach and to fully maximize PBL's promise.

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