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Learning Through Problem Solving

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Learning through problem solving has long been championed by some in the educational sphere (e.g., Dewey, 1938; Kilpatrick, 1918). The latest re-emergence of learning through problem solving coincides with findings in cognitive and educational sciences research showing that transmission models of learning rarely support transfer and application of previously learned information even when learners demonstrate mastery through relatively immediate recitation "tests" of learning. These findings harken back to Whitehead's (1929) discussion of the problem of inert knowledge and lack of transfer or application of relevant prior knowledge in new and appropriate contexts. Learning through problem solving can be contrasted with other types of problem solving research in which the focus is on how people solve problems, including activation of known concepts and procedures (see Greeno, Collins, & Resnick, 1996). In learning through problem solving approaches, the focus is in how people construct new knowledge as they engage in solving problems. These kinds of approaches are important in the learning sciences because they are all theoretically guided designs and provide opportunities to study learning as it unfolds in authentic settings as learners engage with meaningful tasks.

A variety of learning through problem-solving approaches have been developed to address the "inert knowledge problem" (CTGV, 1992; Hmelo-Silver, 2004). For example, research on transfer-appropriate processing examined how people could retrieve problem solutions and ideas based on how they were encoded (e.g., Adams et al., 1988). Building on this, Bransford and Schwartz (1999) argued that early problem-solving experiences could enable learners to see similarities across situations and thus prepare themselves to learn in new situations through both application and adaptation of knowledge (Schwartz, Chase, & Bransford, 2012). Others stressed how knowledge and practices should be framed to foster the expectation that what students learn will be useful in other settings (Engle, 2006). In short, learning through problem-solving approaches promote transfer by helping learners see the relevance of their prior knowledge, preparing them for new learning, and framing that learning as broadly applicable.

Learning through problem solving has been instantiated in a variety of instructional models and designs, including problem- and project-based learning, productive failure, inquiry learning, and design-based learning (Blumenfeld et al., 1991; Kolodner et al., 2003; Linn, McElhaney, Gerard, & Matuk, this volume). Support for learning is embedded in all of these designs in a range of forms, including scaffolds, sequenced and carefully designed tasks, levels, and styles of intervention. Learning through problem-solving instructional designs share two critical features that are advantageous for learning. First, they build integrated conceptual understanding while simultaneously developing problem-solving and self-regulated learning skills (Savery, 2015). When learners confront an ill-structured problem, they must analyze the problem, identify and resolve knowledge deficiencies through self-directed research, and evaluate their proposed solutions (Hmelo-Silver, 2004). In this way, they engage in deep content learning while developing strategies for future learning. Second, engaging in problem solving also provides motivational advantages. Ill-structured, but well-designed complex problems create situational interest. Problems that are complex yet manageable, realistic and relevant, and offer sufficient choice and control, foster intrinsic motivation (Deci, Koestner, & Ryan, 2001; Schmidt, Rotgans, & Yew, 2011). Furthermore, because learning through problem-solving designs is inherently collaborative, learners may also be more motivated to participate (Blumenfeld et al., 1991). Indeed, students attribute increased motivation to enjoying the social interaction as well as to perceived pressure to be contributing to the group (Wijnia, Loyens, & Derous, 2011).

In this chapter we focus on two specific approaches to learning through problem solving that share a number of commonalities: problem-based learning (PBL) and productive failure (PF). Both are stable, empirically supported pedagogical models that emphasize the social nature of learning and focus on robust learning, not short-term performance proficiency. They assume that problem solving is an iterative process that requires time, persistence, and patience. Students learn as they analyze the problem and make solution attempts, initially relying on their existing knowledge and then augmenting that with additional instructional resources. Although PBL and PF have often been contrasted, we consider how these instructional approaches are complementary, drawing on Kapur's (2016) notion of productive success and productive failure.

Productive Success and Failure: A Framework for Understanding Learning Through Problem Solving

Previous research has used instructional designs for learning through problem solving that can be cross-classified along two continua. One refers to the extent to which they are intended to maximize performance in the initial learning task, the other, to the extent to which they maximize learning in the long-term (Kapur, 2008). The four outcomes of this cross-classification are productive success, productive Failure, unproductive success, and unproductive failure. Productive success describes designs that maximize performance in the shorter term as well as maximize learning in the longer term. PF designs may not maximize performance in the short term, but seek to maximize sustained learning in the longer term. Unproductive success results from designs that maximize performance in the shorter term (e.g. through rote memorization) but do not maximize learning in the longer term. Finally, designs that maximize neither short- nor longer-term learning (e.g. unsupported discovery learning) reflect unproductive failure. As indicated above, in this chapter we focus on productive success as exemplified in PBL instructional designs and productive failure designs. Both have shown promise for facilitating transfer for future learning.

Productive Approaches

There is intentionality in the design of the two types of productive approaches to learning through problem solving. The designs differ in terms of the intended short-term problem-solving outcome.

Productive Success. Where success is intended, as in PBL, scaffolding, and facilitation play a central role in the design of the initial problem solving and are seen as critical to outcomes that are productive for future learning (Ertmer & Glazewski, in press; Hmelo-Silver & Barrows, 2008). Scaffolding reduces the cognitive load associated with confronting complex problems and helps students manage the complexity while also learning from their engagement in collaborative problem-solving activities (Blumenfeld et al., 1991). Facilitation refers to kinds of supports that a teacher provides that help guide the learning process (Hmelo-Silver & Barrows, 2008). As students gain expertise and skills, scaffolding then fades as it is needed less (Puntambekar & Hübscher, 2005; Schmidt, Loyens, van Gog, & Paas, 2007).

In addition, the PBL tutorial cycle provides a loose script that helps communicate the PBL process, shown in Figure 21.1 (Collins, 2006; Derry, Hmelo-Silver, Nagarajan, Chernobilsky, & Beitzel, 2006; see also Kollar, Wecker, & Fischer, this volume). PBL facilitators provide key just-in-time guidance through questioning and suggestions (soft scaffolding) or tools to support student inquiry (hard scaffolding), such as graphic organizers and whiteboards that can guide their thinking (Hmelo-Silver, 2004; Puntambekar & Kolodner, 2005). This type of support maximizes both productive success in the initial learning activity, as well as learning in the longer term.

Productive Failure. In contrast to PBL and other success designs, PF does not provide significant initial learning support. Instead students are purposefully engaged in problems requiring concepts they have not yet learned. In this initial problem-solving stage, students explore affordances and constraints of possible solutions. Although they fail in the short term to generate correct solutions, the process of failing prepares them for learning from subsequent instruction and support, provided in the consolidation phase. Consolidation is thought to foster long-term learning by providing opportunities for comparing and contrasting, assembling, and organizing solutions into canonical solutions (Kapur & Bielaczyc, 2012; Schwartz & Martin, 2004).

Learning Mechanisms

Despite the differences in the timing of support for PBL and productive failure, the learning mechanisms are similar. Information processing theory provided the earliest theoretical explanation for the benefits of learning through problem solving—namely, the activation of prior knowledge and transfer-appropriate processing (Adams et al., 1988; Schmidt, 1993). In PBL, learners connect new learning to prior knowledge when they engage in their initial discussion about a problem, thus preparing them for new learning. Transfer-appropriate processing occurs when knowledge encoded in problem-solving contexts is retrieved to solve new problems. In both PBL and PF, students are learning content in the context of a problem-solving situation, and transfer-appropriate processing theory suggests that learners would be more likely to retrieve this knowledge in relevant problem situations.

In PF, the process of differentiating relevant prior knowledge when students generate sub-optimal or incorrect solutions is critical (DeCaro & Rittle-Johnson, 2012; Schwartz, Chase, Oppezzo, & Chin, 2011). It allows students to: (a) notice inconsistencies and draw their attention to gaps in their prior

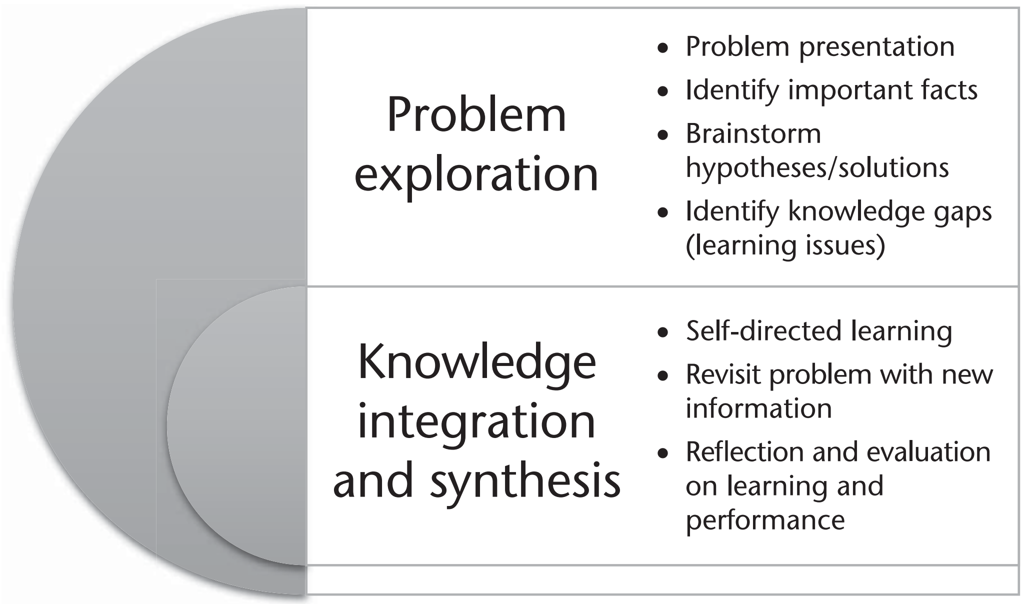

Figure 21.1 PBL Small Group Tutorial Cycle

knowledge (DeCaro & Rittle-Johnson, 2012; Loibl & Rummel, 2014; Ohlsson, 1996); and (b) compare and contrast their generated solutions and the correct solutions during subsequent instruction, enabling students to better encode critical features of the new concept (Kapur, 2014; Schwartz et al., 2011).

More recently, sociocultural theory has broadened our understanding of learning through problem solving. Social constructivist perspectives emphasize active engagement in meaningful learning tasks and the importance of tools in mediating learning (Collins, 2006; Danish & Gresalfi, this volume). As students engage with ill-structured, authentic problems, their learning is supported through facilitator scaffolding of tasks within learners' Zones of Proximal Development (Vygotsky, 1978). This fosters cognitive apprenticeship where students gain problem-solving competencies under the guidance of mentors (Collins, 2006; Quintana et al., 2004; Eberle, this volume). By using conceptual tools, such as language in authentic situations, individuals begin to fully understand their function and complexities. Language itself is a tool learners use to construct meaning and progress in becoming participants in their communities of practice. PBL discourse enables learners to appropriate new disciplinary concepts, vocabulary, and reasoning to engage with other members of the community (Brown et al., 1993; Chernobilsky, DaCosta, & Hmelo-Silver, 2004). As students share what they know, discover what they still need to learn, and form explanations and arguments, their collective thinking becomes visible to the group, inviting discussion and revision.

Research Methods and Findings in PBL and PF

The research literature on PBL is extensive and has used a variety of methods that range from qualitative examinations of curriculum, facilitation, and student development (Bridges, Green, Botelho, & Tsang, 2015; Evensen, Salisbury-Glennon, & Glenn, 2001; Hmelo-Silver & Barrows, 2008) to experimental and quasi-experimental studies of PBL outcomes (e.g., Walker, Leary, & Lefler, 2015). Qualitative methods have included ethnographic, ethnomethodological, and content analysis. Quantitative methods have generally used a range of content and strategy measures. In contrast, PF research methodologies have been largely quantitative. Productive failure research has largely relied on three sequential, yet reinforcing quantitative methodologies. The early work employed design-based research utilizing multiple iterations of design, implementation, and iteration across various contexts and samples to stabilize its design. PF was then tested in classrooms through quasi-experimental investigations. Finally, experimental work was conducted to enable a surgical examination of specific design features and mechanisms (Kapur, 2016). Now that it has achieved a stable design, future qualitative examinations may be employed to better understand the experience of individual learners while engaged in productive failure.

PBL Findings

Because PBL was initially designed to better develop medical reasoning and long-term learning among medical students, much of the early scholarship on its learning gains focused on comparing PBL with direct instruction in medical education. Meta-analytic studies provide mixed findings (e.g., Albanese & Mitchell, 1993; Vernon & Blake, 1993). Vernon and Blake (1993) found that PBL instruction better prepared participants to transfer medical knowledge to solve problems in practice, but was less effective than direct instruction for the acquisition of more basic medical knowledge. However, this advantage may be limited as other researchers have found it to vanish after the second year of medical school (Dochy, Segers, Van den Bossche, & Gijbels, 2003). In addition, when measures of knowledge application are used, PBL demonstrates greater effects over direct instruction (Gijbels, Dochy, Van den Bossche, & Segers, 2005).

PBL has been effectively broadened to include other domains and age groups, including pre-service teachers (Derry et. al., 2006), MBA students (Capon & Kuhn, 2004), and secondary school (CTGV, 1992; Mergendoller, Maxwell, & Bellisimo, 2006), with all of these variations showing positive effects.

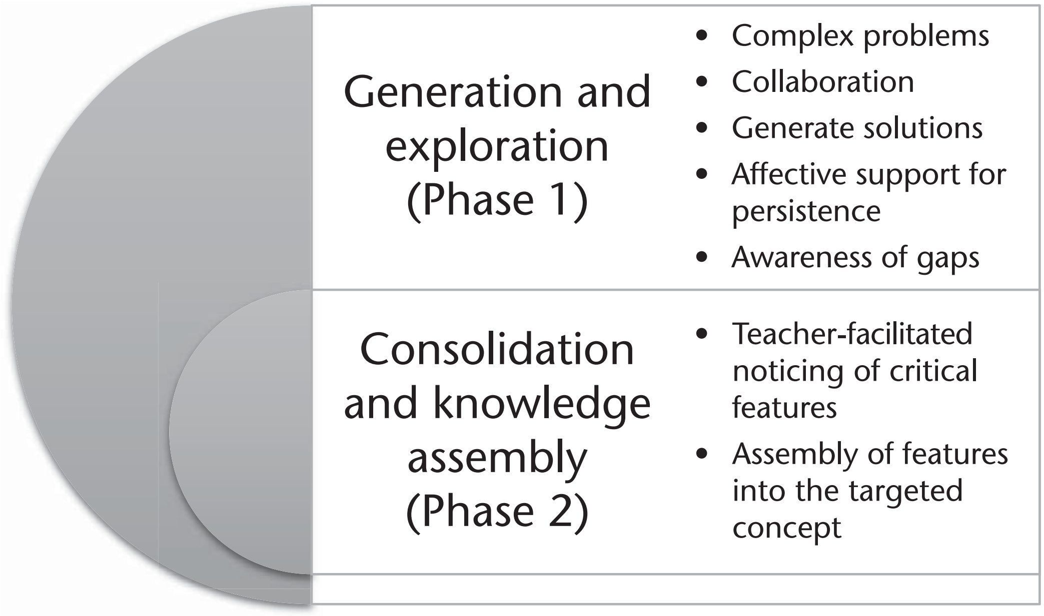

Figure 21.2 Productive Failure Design

A meta-analysis by Walker et al. (2015) found that research across different educational levels and disciplines demonstrated an overall positive but small effect size, but with considerable variability across studies. Moderate effects of PBL were demonstrated when knowledge was assessed at an application level and for strategic performance and design problems. Despite the benefits that aforementioned studies and meta-analysis demonstrated, the effectiveness of PBL continues to be debated. Some researchers warn that the mixed findings across domains suggest that more research is needed to understand the effects of diverse PBL implementation, problem types used, and types of outcomes assessed (Walker et al., 2015). Although the meta-analyses and quantitative studies of PBL tend to show advantages, they are not informative regarding learning processes and facilitation in PBL.

To understand how learning unfolds in PBL discussions, other studies have taken a qualitative turn (cf. Green & Bridges, this volume). For example, Hmelo-Silver and Barrows (2008) demonstrated how medical students engaged in collaborative knowledge building in exploring a complex problem. The facilitator scaffolded the group through asking open-ended questions that helped focus student attention, encourage explanation, causal reasoning, and justification as well as supported groups in monitoring their group dynamics. Students appropriated some of these facilitation functions as they also asked many questions and integrated their self-directed learning. This study also elucidated the important role of shared representations in mediating discussion. Similarly, in teacher professional development, Zhang, Lundeberg, and Eberhardt (2011) studied several PBL groups and their facilitators, finding that facilitators used questioning, revoicing, and a repertoire of strategies to support collaborative advancement of ideas. Yew and Schmidt (2009) found similar evidence of collaborative, self-directed and constructive activity in a polytechnic university. Although much qualitative work in PBL has been conducted with adult learners, Brush and Saye (2008) examined PBL in secondary history classes, finding evidence of students' constructive activity with both cognitive and emotional engagement in historical inquiry. These qualitative studies demonstrate how learning, facilitation, and scaffolding unfold in PBL.

PF Findings

To date, PF research has tended to utilize complex conceptual problems presented to secondary and college-level mathematics and science students in their classroom settings (e.g., DeCaro & Rittle-Johnson, 2012; Kapur, 2012, 2014; Loibl & Rummel, 2014; Schwartz et al., 2011). Findings suggest that students who generate solutions to novel problems before receiving instruction perform significantly better on measures of conceptual understanding and transfer than students who receive instruction prior to engaging in problem solving (Kapur, 2014; Loibl, Roll, & Rummel, 2016). Additionally, PF students who generated multiple solutions performed better on procedural knowledge, conceptual understanding, and transfer items on the posttest. Kapur (2015) called it the "solution generation effect:" the greater the number of solutions generated, the better the learning as measured by performance on the posttest. Kapur argued that the solution generation effect indexes the prior knowledge activation mechanism of PF; that is, when students generate more solutions, relevant prior knowledge gets activated, and such activation prepares students to notice, encode, and retrieve critical features of the targeted concept.

Overall, PBL and PF share a consistent trend in their findings. Compared to direct instruction, both approaches have small or negative effects on basic knowledge acquisition, but positive effects on conceptual understanding and transfer. It is this transfer of prior learning that makes PBL and PF productive pedagogies for robust learning.

Designing for PBL and Productive Failure

As mentioned earlier, the fundamental difference between productive success (exemplified in PBL) and productive failure is in the design of initial problem solving, and where support is provided in the overall learning cycle. Both approaches start with collaborative problem solving, but then the approaches diverge. Although various adaptations of PBL have modified its design in practice, some general design principles of the PBL tutorial process (see Figure 21.1) are key. First, exploration is focused around an ill-structured problem without a single correct answer set in an authentic context. Second, students work in small collaborative groups to identify the problem and design the solution. Students co-construct meaning through integrated exploration across disciplines. Third, teachers act as guides by providing sufficient scaffolding to support student-driven exploration. Finally, reflection and assessment activities are built into the PBL cycle to encourage self-regulated learning (Savery, 2015). Master PBL facilitators employ a range of scaffolds to support students through this learning process (Hmelo-Silver & Barrows, 2008). In the classic PBL model, a whiteboard is used to help students to structure their problem solving and learning by recording facts, ideas, learning issues, and an action plan.

There are several design principles for effective PBL problems (Barrett, Cashman, & Moore, 2011; Hmelo-Silver, 2004; Jonassen & Hung, 2015). First, problems must be sufficiently complex and ill-structured as well as personally relevant to the learners to foster motivation. Second, problems must provide sufficient feedback so learners can evaluate their learning and performance. Good problems promote constructive discussion (Koschmann, Myers, Feltovich, & Barrows, 1994). Jonassen and Hung (2015) examined four problem types typically used in PBL: diagnostic, decision-making, situated cases/policy, and design problems. Design problems can be particularly fruitful, engaging learners in constructing an artifact based on functional specifications (e.g., Jordan & McDaniel, 2014; Kolodner et al., 2003). Design problems may be effective because of the feedback such problems afford.

Problems for the PF approach tend to be sufficiently complex to afford multiple representations and solution methods by drawing on various formal and informal resources. They can be both well-structured (e.g., Kapur, 2014; Kapur & Bielaczyc, 2012) or ill-structured (e.g., Kapur, 2008), but need to be designed with an intuitive and affective hook, embody multiple contrasts that help students notice critical features, and use variant–invariant relations so that student-generated solutions do not lead to successful solutions. This failure then provides the opportunity to compare and contrast the affordances and constraints of their failed and sub-optimal solutions. Ill-structured PBL problems can foster problem-relevant collaborative discussion; however, groups may need more support to make this interaction productive (Kapur & Kinzer, 2007).

Prior knowledge represents the most critical design component of PF, as it primes learners for future learning. The four core mechanisms are: "a) activation and differentiation of prior knowledge, b) attention to critical conceptual features of the targeted concepts, c) explanation and elaboration of these features, and d) organization and assembly of the critical conceptual features into the targeted concepts" (Kapur & Bielaczyc, 2012, p. 75). Students engage in this process through two phases (Figure 21.2): a problem-solving phase (Phase 1) followed by a consolidation phase (Phase 2). In Phase 1, students generate and explore the affordances and constraints of multiple representations and solutions. They then organize and assemble their generated solutions into canonical solutions in Phase 2.

Technology in Learning Through Problem Solving

Some of the challenges for learning through problem solving have involved creating rich problem contexts, scaffolding, providing access to information resources, and communication modalities. Technology has played a role in addressing these challenges. It can be used to provide context, scaffolds, information resources, and spaces for visualizing and co-constructing ideas. In a learning sciences course for pre-service teachers, Derry et al. (2006) created an online PBL system that included problem contexts with scenarios that included both a videocase of a student or classroom as well as a problem statement that set the students' goal to redesign the lesson or design a similar one, based on learning sciences principles. They created scaffolds through the use of an eight-step activity structure and prompts to organize the group problem solving in an online whiteboard. The cases included links to a learning sciences hypermedia as a starting point to help guide learners to productive learning issues. In a data analysis course, Holmes, Day, Park, Bonn, and Roll (2014) created the Invention Support Environment to provide contrasting cases and guidance for the invention phase of productive failure.

Other technological tools such as interactive whiteboards can help groups visualize their thinking and organize their process as students generate and refine their solutions (Bridges et al., 2015; Lu, Lajoie, & Wiseman, 2010; Green & Bridges, this volume). Likewise, facilitators could benefit from technological tools that automate some scaffolding, provide learning analytics data, and enable faster feedback to students (Blumenfeld et al., 1991; Rosé, this volume). Understanding the roles for technology is an emerging area for both PBL and PF.

Implications for the Learning Sciences

We gain many insights from jointly considering productive success and productive failure under the umbrella of learning through problem solving. Both approaches help learners understand how knowledge and practices can be tools for thinking, problem solving, and participating in a community of practice. Neither approach focuses on the final solution to the problem, but on how the process of working through carefully designed problems prepares learners for future learning. Although learning through problem-solving approaches has been critiqued for being minimally guided and increasing cognitive load (Kirschner, Sweller, & Clark, 2006), the participant structures, routines, and scaffolding in learning through problem solving help support productive success (Hmelo-Silver, Duncan, & Chinn, 2007).

In many ways, the two approaches to learning through problem solving are two sides of the same coin. Both involve having learners begin with a problem they do not know how to solve but must learn new content, skills, and disciplinary practices along the way. Social practices and complex learning environments are part and parcel of both of these pedagogical designs. In PBL, the goal is to scaffold the students towards productive success, whereas in productive failure, the failure that occurs is an opportunity for learning. In PBL the opportunity for learning comes from identifying knowledge gaps. In the end, we argue that the similarities among different models of learning through problem solving are just as important as the distinctions. Indeed, "productive success could well be conceived as a design that embodies iterative cycles of productive failure" (Kapur, 2016, p. 297). We argue that it is critical to be intentional in the design of the task and the timing of support with an eye towards learning goals. In future design and research efforts, we need to be exploring under what circumstances and for whom different approaches to learning through problem solving are effective and why. How does the designed system function to support learning? Learning through problem-solving approaches provide effective designs for learning, but they also provide contexts to study complex learning in action, providing important implications for research and practice. Future approaches to learning through problem solving will depend on the ability of researchers to examine adaptations of the models in practice within different disciplinary foci, and across problem solvers that reflect diverse demographic characteristics (e.g., age, linguistic and experiential backgrounds, socioeconomic status, and rural–urban geographies).

Further Readings

Blumenfeld, P. C., Soloway, E., Marx, R. W., Krajcik, J. S., Guzdial, M., & Palincsar, A. (1991). Motivating project-based learning: Sustaining the doing, supporting the learning. *Educational Psychologist, 26*(3–4), 369–398.

This article overviews motivational and instructional issues inherent in project-based learning and provides suggestions for how technology may be used to support them. The authors contend that student interest in projects can be bolstered by variety, student control, opportunities for collaboration, and teacher scaffolding.

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review, 16*(3), 235–266.

This article provides an overview of goals, core components, and scholarship of problem-based learning. This article also addresses the PBL scholarship that has provided mixed learning results and calls for additional research in diverse settings beyond the medical school context.

Hmelo-Silver, C. E., & Barrows, H. S. (2008). Facilitating collaborative knowledge building. *Cognition and Instruction, 26*(1), 48–94.

This empirical study of student and facilitator discourse examines how expertly facilitated PBL can develop knowledge-building practices among students. Attention to core conditions of knowledge building, such as student engagement in constructing and transforming knowledge as well as student control over learning, can be supported.

Kapur, M. (2016). Examining productive failure, productive success, unproductive failure, and unproductive success in learning. *Educational Psychologist, 51*(2), 289–299.

This article reviews four theoretical categories of success and failure in learning: productive failure, productive success, unproductive success, and unproductive failure. While clear definitions, empirical evidence, and specific design considerations are provided for each, abandoning a strict, dichotomous understanding of the four categories; attention to cognitive, social, and cultural mechanisms; and assessing students' pre-existing knowledge are encouraged when designing for learning.

Walker, A., Leary, H., Ertmer, P. A., & Hmelo-Silver, C. (2015). Epilogue: The future of PBL. In A. Walker, H. Leary, C. Hmelo-Silver, & P. A. Ertmer (Eds.), *Essential readings in problem-based learning: Exploring and extending the legacy of Howard Barrows* (pp. 373–376). West Lafayette, IN: Purdue University Press.

This chapter provides an overview of how past and present conceptions of problem-based learning will inform its future iterations.

NAPLeS Resources

Hmelo-Silver, C. E. *Problem-based learning* [Webinar]. In *NAPLeS video series*. Retrieved October 19, 2017, from http://isls-naples.psy.lmu.de/intro/all-webinars/hmelo-silver/index.html

References

Adams, L., Kasserman, J., Yearwood, A., Perfetto, G., Bransford, J., & Franks, J. (1988). The effect of fact versus problem oriented acquisition. *Memory & Cognition*, *16*, 167–175.

Albanese, M., & Mitchell, S. (1993). Problem-based learning: A review of the literature on its outcomes and implementation issues. *Academic Medicine*, *68*, 52–81.

Barrett, T., Cashman, D., & Moore, S. (2011). Designing problems and triggers in different media. In T. Barrett & S. Moore (Eds.), *New approaches to problem-based learning: Revitalising your practice in higher education* (pp. 18–35). New York: Routledge.
Blumenfeld, P. C., Soloway, E., Marx, R. W., Krajcik, J. S., Guzdial, M., & Palincsar, A. (1991). Motivating project-based learning: Sustaining the doing, supporting the learning. *Educational Psychologist, 26*(3–4), 369–398.
Bransford, J. D., & Schwartz, D. (1999). Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education*, *24*, 61–100.
Bridges, S., Green, J., Botelho, M., & Tsang, P. C. (2015). Blended learning and PBL: An interactional ethnographic approach to understanding knowledge construction in situ In A. Walker, H. Leary, C. Hmelo-Silver, & P. A. Ertmer (Eds.), *Essential readings in problem-based learning: Exploring and extending the legacy of Howard S. Barrows* (pp. 107–130). West Lafayette, IN: Purdue University Press.
Brown, A. L., Ash, D., Rutherford, M., Nakagawa, K., Gordon, A., & Campione, J. C. (1993). Distributed expertise in the classroom. In G. Salomon (Ed.), *Distributed cognitions* (pp. 188–228). New York: Cambridge University Press.
Brush, T., & Saye, J. (2008). The effects of multimedia-supported problem-based inquiry on student engagement, empathy, and assumptions about history. *Interdisciplinary Journal of Problem-Based Learning*, *2*(1), 4.
Capon, N., & Kuhn, D. (2004). What's so good about problem-based learning? *Cognition and Instruction*, *22*(1), 61–79.
Chernobilsky, E., DaCosta, M. C., & Hmelo-Silver, C. E. (2004). Learning to talk the educational psychology talk through a problem-based course in educational psychology. *Instructional Science*, *32*, 319–356.
Collins, A. (2006). Cognitive apprenticeship. In K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 47–60). New York: Cambridge University Press.
CTGV. (1992). The Jasper series as an example of anchored instruction: Theory, program description and assessment data. *Educational Psychologist*, *27*, 291–315.
Danish, J., & Gresalfi, M. (2018). Cognitive and sociocultural perspective on learning: tensions and synergy in the Learning Sciences. In F. Fischer, C. E. Hmelo-Silver, S. R. Goldman, & P. Reimann (Eds.), *International handbook of the learning sciences* (pp. 34–43). New York: Routledge.
DeCaro, M. S., & Rittle-Johnson, B. (2012). Exploring mathematics problems prepares children to learn from instruction. *Journal of Experimental Child Psychology*, *113*, 552–568.
Deci, E. L., Koestner, R., & Ryan, R. M. (2001). Extrinsic rewards and intrinsic motivation in education: Reconsidered once again. *Review of Educational Research*, *71*, 1–27.
Derry, S. J., Hmelo-Silver, C. E., Nagarajan, A., Chernobilsky, E., & Beitzel, B. (2006). Cognitive transfer revisited: Can we exploit new media to solve old problems on a large scale? *Journal of Educational Computing Research*, *35*, 145–162.
Dewey, J. (1938). *Experience and education* (Kappa Delta Phi Lecture Series) New York: Macmillan.
Dochy, F., Segers, M., Van den Bossche, P., & Gijbels, D. (2003). Effects of problem-based learning: A meta-analysis. *Learning and Instruction*, *13*(5), 533–568.
Eberle, J. (2018). Apprenticeship learning. In F. Fischer, C. E. Hmelo-Silver, S. R. Goldman, & P. Reimann (Eds.), *International handbook of the learning sciences* (pp. 44–53). New York: Routledge.
Engle, R. A. (2006). Framing interactions to foster generative learning: A situative explanation of transfer in a community of learners classroom. *Journal of the Learning Sciences*, *15*(4), 451–498.
Ertmer, P. A., & Glazewski, K. D. (in press). Scaffolding in PBL environments: Structuring and problematizing relevant task features. To appear in W. Hung, M. Moallem, N. Dabbagh (Eds). *Wiley handbook of problem-based learning*.
Evensen, D. H., Salisbury-Glennon, J., & Glenn, J. (2001). A qualitative study of 6 medical students in a problem-based curriculum: Towards a situated model of self-regulation. *Journal of Educational Psychology*, *93*, 659–676.
Gijbels, D., Dochy, F., Van den Bossche, P., & Segers, M. (2005). Effects of problem-based learning: A meta-analysis from the angle of assessment. *Review of Educational Research*, *75*(1), 27–61.
Green, J. L., & Bridges, S.M. (2018) Interactional ethnography. In F. Fischer, C. E. Hmelo-Silver, S. R. Goldman, & P. Reimann (Eds.), *International handbook of the learning sciences* (pp. 475–488). New York: Routledge.
Greeno, J. G., Collins, A. M., & Resnick, L. B. (1996). Cognition and learning. In D. Berliner & R. Calfee (Eds.), *Handbook of educational psychology* (pp. 15–46). New York: Macmillan.
Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review*, *16*(3), 235–266.
Hmelo-Silver, C. E., & Barrows, H. S. (2008). Facilitating collaborative knowledge building. *Cognition and Instruction*, *26*(1), 48–94.
Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist*, *42*, 99–107.

Holmes, N., Day, J., Park, A. H., Bonn, D., & Roll, I. (2014). Making the failure more productive: Scaffolding the invention process to improve inquiry behaviors and outcomes in invention activities. *Instructional Science*, *42*(4), 523–538.

Jonassen, D., & Hung, W. (2015). All problems are not created equal: Implications for problem-based learning. In A. Walker, H. Leary, C. Hmelo-Silver, & P. A. Ertmer (Eds.), *Essential readings in problem-based learning: Exploring and extending the legacy of Howard S. Barrows* (pp. 69–84). West Lafayette, IN: Purdue University Press.

Jordan, M. E., & McDaniel, Jr, R. R. (2014). Managing uncertainty during collaborative problem solving in elementary school teams: The role of peer influence in robotics engineering activity. *Journal of the Learning Sciences*, *23*(4), 490–536.

Kapur, M. (2008). Productive failure. *Cognition and Instruction*, *26*(3), 379–424.

Kapur, M. (2012). Productive failure in learning the concept of variance. *Instructional Science*, *40*, 651–672.

Kapur, M. (2014). Productive failure in learning math. *Cognitive Science*, *38*(5), 1008–1022.

Kapur, M. (2015). Learning from productive failure. *Learning: Research and Practice*, *1*(1), 51– 65.

Kapur, M. (2016). Examining productive failure, productive success, unproductive failure, and unproductive success in learning. *Educational Psychologist*, *51*(2), 289–299.

Kapur, M., & Bielaczyc, K. (2012). Designing for productive failure. *Journal of the Learning Sciences*, *21*(1), 45–83.

Kapur, M., & Kinzer, C. K. (2007). Examining the effect of problem type in a synchronous computer-supported collaborative learning (CSCL) environment. *Educational Technology Research and Development*, *55*(5), 439–459.

Kilpatrick, W. H. (1918). The project method. *Teachers College Record*, *19*, 319–335.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work. *Educational Psychologist*, *41*, 75–86.

Kollar, I., Wecker, C., & Fischer, F. (2018). Scaffolding and scripting (computer-supported) collaborative learning. In F. Fischer, C. E. Hmelo-Silver, S. R. Goldman, & P. Reimann (Eds.), *International handbook of the learning sciences* (pp. 340–350). New York: Routledge.

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., Puntambekar, S., & Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by design(tm) into practice. *Journal of the Learning Sciences*, *12*(4), 495–547.

Koschmann, T. D., Myers, A., Feltovich, P. J., & Barrows, H. S. (1994). Using technology to assist in realizing effective learning and instruction: A principled approach to the use of computers in collaborative learning. *Journal of the Learning Sciences*, *3*(3), 227–264.

Linn, M. C., McElhaney, K. W., Gerard, L., & Matuk, C. (2018). Inquiry learning and opportunities for technology. In F. Fischer, C. E. Hmelo-Silver, S. R. Goldman, & P. Reimann (Eds.), *International handbook of the learning sciences* (pp. 221–233). New York: Routledge.

Loibl, K., Roll, I., & Rummel, N. (2016). Towards a theory of when and how problem solving followed by instruction supports learning. *Educational Psychology Review*, *29*(4), 693–715. doi:10.1007/s10648-016-9379-x

Loibl, K., & Rummel, N. (2014). Knowing what you don't know makes failure productive. *Learning and Instruction*, *34*, 74–85.

Lu, J., Lajoie, S. P., & Wiseman, J. (2010). Scaffolding problem-based learning with CSCL tools. *International Journal of Computer Supported Collaborative Learning*, *5*(3), 283–298.

Mergendoller, J. R., Maxwell, N. L., & Bellisimo, Y. (2006). The effectiveness of problem-based instruction: A comparative study of instructional method and student characteristics. Interdisciplinary *Journal of Problem-based Learning*, *1*, 49–69.

Ohlsson, S. (1996). Learning from performance errors. *Psychological Review*, *103*, 241–262.

Puntambekar, S., & Hubscher, R. (2005). Tools for scaffolding students in a complex learning environment: What have we gained and what have we missed? *Educational Psychologist*, *40*(1), 1–12.

Puntambekar, S., & Kolodner, J. L. (2005). Toward implementing distributed scaffolding: Helping students learn science from design. *Journal of Research in Science Teaching*, *42*(2), 185–217.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., et al. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences*, *13*(3), 337–386.

Rosé, C. P. (2018). Learning analytics in the Learning Sciences. In F. Fischer, C. E. Hmelo-Silver, S. R. Goldman, & P. Reimann (Eds.), *International handbook of the learning sciences* (pp. 511–519). New York: Routledge.

Savery, J. R. (2015). Overview of problem-based learning: Definitions and distinctions. In A. Walker, H. Leary, C. Hmelo-Silver, & P. A. Ertmer (Eds.), *Essential readings in problem-based learning: Exploring and extending the legacy of Howard S. Barrows* (pp. 5–16). West Lafayette, IN: Purdue University Press.

Schmidt, H. G. (1993). Foundations of problem-based learning: Some explanatory notes. *Medical Education*, *27*, 422–432.

Schmidt, H. G., Loyens, S. M., Van Gog, T., & Paas, F. (2007). Problem-based learning is compatible with human cognitive architecture: Commentary on Kirschner, Sweller, and Clark (2006). *Educational Psychologist*, *92*, 91–97.

Schmidt, H. G., Rotgans, J. I., & Yew, E. H. (2011). The process of problem-based learning: What works and why. *Medical Education*, *45*(8), 792–806.

Schwartz, D., Chase, C. C., & Bransford, J. (2012). Resisting overzealous transfer: Coordinating previously successful routines with needs for new learning. *Educational Psychologist*, *47*(3), 204–214.

Schwartz, D., Chase, C. C., Oppezzo, M. A., & Chin, D. B. (2011). Practicing versus inventing with contrasting cases: The effects of telling first on learning and transfer. *Journal of Educational Psychology*, *103*, 759–775.

Schwartz, D., & Martin, T. (2004). Inventing to prepare for future learning: The hidden efficiency of encouraging original student production in statistics instruction. *Cognition and Instruction*, *22*, 129–184.

Vernon, D. T. A., & Blake, R. L. (1993). Does problem-based learning work? A meta-analysis of evaluative research. *Academic Medicine*, *68*, 550–563.

Vygotsky, L. S. (1978). *Mind in society: The development of higher mental process*. Cambridge, MA: Harvard University Press.

Walker, A., Leary, H., & Lefler, M. (2015). A meta-analysis of problem-based learning: Examination of education levels, disciplines, assessment levels, problem types, and reasoning strategies. In A. Walker, H. Leary, C. Hmelo-Silver, & P. A. Ertmer (Eds.), *Essential readings in problem-based learning: Exploring and extending the legacy of Howard S. Barrows* (pp. 303–330). West Lafayette, IN: Purdue University Press.

Whitehead, A. N. (1929). *The aims of education and other essays*. New York: Macmillan.

Wijnia, L., Loyens, S. M., & Derous, E. (2011). Investigating effects of problem-based versus lecture-based learning environments on student motivation. *Contemporary Educational Psychology*, *36*(2), 101–113.

Yew, E. H., & Schmidt, H. G. (2009). Evidence for constructive, self-regulatory and collaborative processes in problem-based learning. *Advances in Health Sciences Education*, *14*, 251–273.

Zhang, M., Lundeberg, M., & Eberhardt, J. (2011). Strategic facilitation of problem-based discussion for teacher professional development. *Journal of the Learning Sciences*, *20*, 342–394.