Understanding Learners' Challenges and Scaffolding their Ill-structured Problem Solving in a Technology-Supported Self-Regulated Learning Environment

Victor Law, Xun Ge, and Kun Huang

Introduction

It has been nearly three decades since Sinnott (1989) published her influential book *Everyday Problem Solving*. Everyday problems are also known as ill-structured problems that we encounter every day in our life, which are situated, complicated, and intertwined. Ill-structured problems may involve multiple paths to multiple solutions, or they may not have solutions at all (Jonassen, 2004). Ill-structured problems are distinguished from well-structured problems that have clearly defined goals and can be solved by following step-by-step procedures, as often found in school textbooks (Jonassen, 1997). Whether we recognize it or not, ill-structured problems permeate every aspect of our life.

As a key twenty-first-century skill, problem solving is gaining increasing attention in education and workforce development (e.g., Bulu & Pedersen, 2010; Casner-Lotto & Barrington, 2006; Chen, 2010; Milbourne & Wiebe, 2017). Arguably, if we fail to prepare learners to become effective problem solvers today, we would fail to cultivate a generation of creative thinkers and innovative problem solvers that could contribute significantly and dynamically to tomorrow's world. Today's educators generally agree that it is insufficient to focus on rule-based, well-structured problems

V. Law (✉)
Program of Organization, Information, and Learning Sciences, University of New Mexico, Albuquerque, NM, USA
e-mail: vlaw@unm.edu

X. Ge
Department of Educational Psychology, University of Oklahoma, Norman, OK, USA
e-mail: xge@ou.edu

K. Huang
Department of Curriculum and Instruction, University of Kentucky, Lexington, KY, USA
e-mail: K.Huang@uky.edu

M. J. Bishop et al. (eds.), *Handbook of Research in Educational Communications and Technology*, https://doi.org/10.1007/978-3-030-36119-8_14

only; we need to invest more effort on providing learners with rich and authentic learning experiences that help to cultivate their everyday problem-solving skills (Kim & Hannafin, 2011). Yet, conventional school curricula and instructional approaches often do not adequately prepare learners to solve ill-structured problems. As a result, learners are often unable to transfer their knowledge, that is, they often cannot apply what they have learned from school to solve problems in real-world situations (Feltovich, Spiro, Coulson, & Feltovich, 1996).

Although the disconnection between the school and the outside world was noticed decades ago, this situation has not been significantly improved. While today's school curricula have incorporated key problem-solving skills (e.g., reasoning, reflection, decision making) and adopted more student-centered learning approaches (e.g., problem-based learning, project-based learning, guided inquires), there are still discrepancies between the ideal of instructional design and the reality of actual instructional practices. Numerous factors can affect the execution of student-centered learning focusing on ill-structured problem-solving, including both teacher factors and learner factors (e.g., learners' internal processes and external factors, Ge & Hardre, 2010). Most literature on ill-structured problem solving anchored on an understanding of the expert model (i.e., the knowledge schema of an expert), with the hope of providing scaffolding to learners (Jonassen, 1997), while little research has attempted to understand learners' difficulties in the process of solving ill-structured problems. In order to effectively scaffold ill-structured problem solving, it is important that we understand both the expert model and the learner model. Apart from understanding learner challenges in cognition and metacognition, it is also essential to understand those issues concerning learners' other internal processes (e.g., motivation and beliefs) involved in solving ill-structured problems (Ge & Chua, In Press; Ge & Hardre, 2010).

Purpose

The purpose of this chapter is to understand learners' challenges in ill-structured problem solving and identify effective strategies and tools to scaffold their problem-solving processes. The following goals serve to organize the chapter: (1) presenting an updated expert model of ill-structured problem solving by critically synthesizing the literature on self-regulation and problem-solving models (e.g., Ge, Law, & Huang, 2016; Robertson, 2017), (2) identifying learner challenges in the ill-structured problem-solving processes by comparing their performance with the expert model, (3) proposing a scaffolding framework with strategies and tools to address learner challenges. In achieving the third goal, we present the scaffolding framework in two separate parts. Part 1 focuses on the *design* of scaffolding that addresses key stages of problem solving, the iterative self-regulation processes within the stages, and learners' motivation and beliefs. Part 2 focuses on *facilitation*, that is, the dynamic scaffolding provided by the teacher, facilitator, or peer learners. In other words, Part 1 focuses on *hard* scaffolding (Saye & Brush, 2002) such as pre-defined, pre-designed, or pre-planned scaffolding (e.g., prompts, templates, canned feedback), while Part 2 focuses on *soft* scaffolding (adaptive, just-in-time scaffolding afforded by the teacher, facilitator, or peers). Finally, an example is provided to illustrate how to incorporate both hard and soft scaffolding tools in an ill-structured problem-solving task.

Expert Model of Self-Regulated, Ill-Structured Problem Solving

Research on how experts solve problems provides insights into the nature of cognitive processes in problem solving (Bransford, Brown, Cocking, 2003). There is a wealth of literature on how experts solve problems (i.e., expert model) (e.g., Lajoie, 1993; Shute & Psotka, 1996). The expert problem solving is compared with a novice's problem solving (i.e., student model) in order to identify gaps and effective strategies to bridge the gaps (Lajoie, 1993; Shute & Psotka, 1996). In this section, we begin by reviewing and comparing a few prominent expert models in ill-structured problem solving, which then lead into the updated expert model, with a particular focus on self-regulated, iterative nature of problem solving while taking into consideration the roles of learners' epistemic beliefs and motivation (see Ge, Law, & Huang, 2016).

Ill-structured problems often have a vague initial state or unclear goals, and the means and paths to solve the problems are not clearly defined, which require problem solvers to identify and determine unstated goals and constraints in the problem-solving process (Jonassen, 1997). Since the 1980s, researchers proposed various models to capture how experts solve ill-structured problems (Ge & Land, 2003; Jonassen, 1997; Sinnott, 1989; Voss & Post, 1988). Table 1 summarizes the key problem-solving processes described in some ill-structured problem-solving models:

Although the key processes vary in different models, all the models include two main processes: problem representation and solution generation, with essential components such as monitoring and evaluation. In the problem representation stage, solvers explore the problem space and connect their prior knowledge in an attempt to develop an understanding of the problem. In the solution generation stage, learners develop, implement, and justify plausible solutions. All of the models suggest that problem solvers have to engage in both cognitive and metacognitive processes, but only one model (Sinnott, 1989) pointed out motivation and emotion as important non-cognitive processes in ill-structured problem solving.

Recently, Ge, Law, and Huang (2016) proposed an updated ill-structured problem-solving model by highlighting the iterative nature of ill-structured problem solving. The model depicts ill-structured problem solving as a series of self-regulation processes that feed from one stage to another (see Fig. 1). Problem solvers are required to self-regulate themselves throughout the problem representation and solution generation stages. Moreover, the evaluation and judgment of their

Table 1 Key expert models on ill-structured problem solving

Author(s)/year	Problem-solving processes
Voss & Post (1988)	Problem representation Problem solution
Sinnott (1989)	Construction of problem space Generation of solution Monitors Memories Non-cognitive elements
Jonassen (1997)	Articulate problem space and contextual constraints Identify and clarify alternative opinions, positions, and perspectives of stakeholders Generate possible problem solutions Assess the viability of alternative solutions by constructing arguments and articulating personal beliefs Monitor the problem space and solution options Implement and monitor the solution Adapt the solution
Ge & Land (2003)	Problem representation Problem solution Making justification Monitoring and evaluation

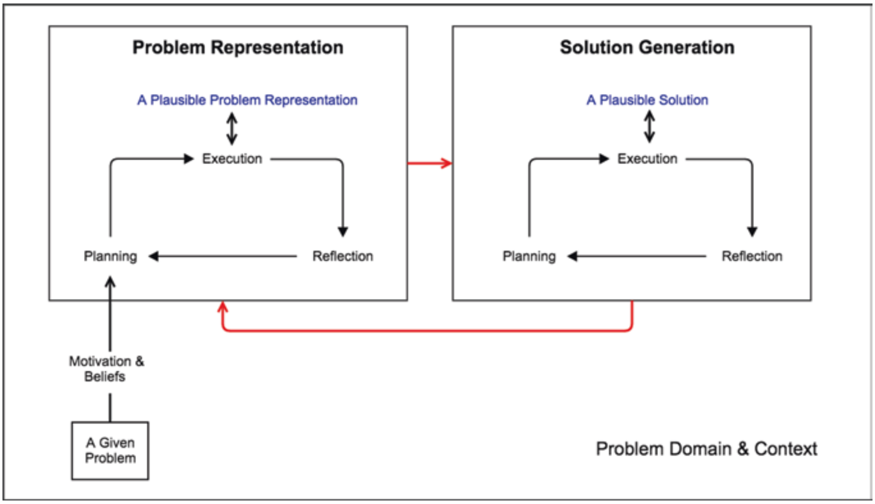

Fig. 1 An updated self-regulated ill-structured problem-solving model

problem representation or solution generation will trigger problem solvers to move between stages. For instance, when problem solvers find a solution unsatisfactory upon evaluation, they may revisit and further redefine the problem representation. Expert problem solvers frequently regulate and refine their problem representations and solutions throughout the problem-solving process.

In addition to highlighting the iterative nature of ill-structured problem solving, motivation and beliefs have been integrated as essential components in the Ge, Law, and Huang (2016) model (Fig. 1). Motivation and beliefs in learning have gained increasing recognition in recent educational research (Boekaerts, 1997; Muis, 2007; Pintrich, Marx, & Boyle, 1993). Accumulating evidence suggests that motivation and beliefs play essential roles in learning, which we address in the next section as we analyze and discuss learners' challenges in ill-structured problem solving.

Learners' Challenges in Solving Ill-Structured Problems

Following the discussion on the expert model of ill-structured problem solving, we now direct our attention to the student model (Lajoie, 1993; Shute & Pskota, 1996), which is grounded in learners' difficulties or challenges in solving ill-structured problems. Based on a review of the literature, we first present five challenges learners commonly experience *within* the two problem-solving stages: problem representation and the solution generation; next, we identify learners' challenges in their navigation *between* the two stages.

Learners' Challenges Within Problem Representation and Solution Generation Stages

Challenges in Applying Prior Knowledge

When faced with an ill-structured problem, learners draw on prior knowledge as a frame of reference to help with problem representation, and later, solution generation (Ertmer et al., 2008). A part of prior knowledge is the existing schema in the problem domain, which learners are often lacking (Rumelhart & Norman, 1978). For example, if learners need to design a training plan while having little prior knowledge about teaching and learning, they may have difficulties identifying key aspects of the problem. Similarly, in the solution generation stage, due to a lack of procedural knowledge in instructional design, learners may not execute the instructional design task effectively. Furthermore, they may not be able to identify appropriate resources and strategies to facilitate the process, which may eventually impact the solution, that is, the training plan.

When domain knowledge is lacking, learners often fill in with another part of their prior knowledge—personal experience that may bear certain resemblance with the problem, in an effort to make sense of the problem and generate solutions. In some cases, the personal experience may help steer toward an initial problem representation that acts as a springboard for further development. For instance, teachers who are new to instructional design often use their past lesson-planning experience to interpret and perform an instructional design task (Ge, Chen, & Davis, 2005).

In other cases, prior experience may lock learners in fixed problem representations or solutions without necessary updates to a more appropriate version. For example, when faced with the problem, "How to handle expired food?" A learner who always throws away expired food may interpret the problem as a need to find evidence to support his personal experience, and thus directs his solution generation effort accordingly (Huang, Law, Ge, & Yu, 2017).

Challenges in Cognitive Processing

To develop a precise representation of a problem, problem solvers need to engage in articulating problem space and constraints, synthesizing information, and identifying the relationships among issues in the problem (Jonassen, 1997). However, learners often do not engage in all or some of the cognitive processes (Ertmer & Stepich, 2005). As a result, they often cannot identify all the relevant constraints nor understand the relationships among different variables of a problem (Dörner, 1987). Due to problems' complexity and ill-structuredness, learners often have difficulties predicting the development of complex problems which may grow exponentially (Dörner, 1987), which, in turn, can lead to high cognitive loads (Marcus, Cooper, & Sweller, 1996). To cope with the cognitive loads, some learners may choose to focus on salient surface features of a problem while filtering out less salient but more important and relevant information, which may subsequently affect the solution generation stage (Ertmer et al., 2009; Jonassen, 2007). For example, when designing instructions, some learners may focus only on the content of the training, while disregarding other important information such as learners and the context of learning, even though they are required to analyze learners and context of the instruction. As a result, they are not able to synthesize all the relevant information when designing instructions.

Challenges in Regulative Thinking

Regulative thinking is critical in ill-structured problem solving. Shin, Jonassen, and McGee (2003) found that regulation of cognition predicted ill-structured problem solving in astronomy simulations. At the problem representation stage, regulative thinking focuses on the monitoring, justification, and adoption of a plausible problem representation. However, many learners go through the stage rather quickly, without taking time to consciously monitor the coordination among several interrelated components at this stage: the information about the problem, the recall of prior knowledge, and the emerging problem representations. For example, upon reading task materials, it is common that problem solvers do not activate all the relevant prior knowledge at once. Yet, some learners do not consciously revisit the task information to determine whether they have missed recalling any relevant information. Furthermore, upon formulating an understanding of the problem, learners often do not consciously examine their understanding against the task information and their prior knowledge. As such, they miss the opportunity to identify and fill any gaps, which could otherwise lead to an enriched problem representation. Similar challenges exist in the solution generation stage, where regulative thinking can help learners to monitor the solution progress iteratively and evaluate, select, and justify solutions. Learners often approach the solution stage in a linear manner and settle on a solution without evaluating its effectiveness or considering alternative solutions (Quintana et al., 2004).

Challenges of Unproductive Epistemic Beliefs

In addition to cognitive factors, learners' epistemic beliefs have an important bearing in how they conceptualize a learning task (Muis, 2007). As an important antecedent of learning, epistemic beliefs refer to our beliefs about the nature of knowledge and knowing (Hofer & Pintrich, 1997). Schraw, Dunkle, and Bendixen (1995) found that learners' epistemic beliefs are related to their performance in ill-structured problem solving. Epistemic beliefs can be a reason underlying the aforementioned learners' challenges in solving ill-structured problems. For example, over-reliance on personal experience to interpret a problem while discounting or rejecting new information is likely due to unproductive epistemic beliefs about the construction of knowledge (Huang, Law et al., 2017). Furthermore, the lack of regulative monitoring and coordination among one's prior knowledge, task information, and problem representation is also likely due to epistemological standards originated from immature epistemic beliefs (Muis, 2007). As such, learners do not see potential misalignment among the three, which can lead to an inaccurate judgment of the plausibility of a problem representation. Epistemic beliefs can also influence the solution generation stage. For example, learners of immature epistemic beliefs may seek information and resources to support their planned solution, while not willing to seek or to ignore the information that may challenge their original solution plan (Chinn & Brewer, 1993; Huang, Ge, & Law, 2017).

Challenges in Learners' Motivation

In addition to learners' fundamental beliefs, their motivation also plays a role in problem representation and solution generation. For example, in solving an information problem, those learners whose goal was to avoid showing incompetence may represent the problem as the search for a perfect website that contains the answer to the problem (Wallace, Kupperman, Krajcik, & Soloway, 2000). At the solution generation stage, these learners tend to use ineffective search strategies (Zhou, 2013b). In addition to achievement goals, learners' adopted identity in a problem situation can affect how they approach a problem. For example, in working on the same software design project, some learners positioned themselves as software developers working for a client, while others took on the role of learners who were trying to earn a course grade; the identities, in turn, affected how they represented and approached the problem-solving task (Ge, Huang, & Dong, 2010).

Learners' Challenges Navigating Between Problem Representation and Solution Generation

A critical process in ill-structured problem solving is the navigation between two stages: problem representation and solution generation (Ge, Law, & Huang, 2016). The navigations between the processes are precisely where learners experience great challenges. The challenges are centered on three key areas. First, learners often do not judge or misjudge the plausibility of a problem representation and move hastily to the solution stage (Ertmer & Stepich, 2005). This is likely due to the lack of domain knowledge (e.g., applicable domain standards), lack of elaboration of thoughts, lack of regulative monitoring (between problem representation, prior knowledge, and problem information), as well as immature epistemic beliefs, which can lead to the lack of monitoring of one's problem representation.

The second challenge lies in the alignment between problem representation and solution generation. In a study that examined ill-structured problem solving in learners' handling of instructor's qualitative feedback, Huang, Ge et al. (2017) found that some students' solutions were not aligned with their problem representation, that is, their understanding of instructor's feedback. While this case shows a clear lack of regulative monitoring, Huang, Ge et al.'s (2017) findings suggested that immature epistemic beliefs might be the root cause.

The third challenge for learners is the multiple iterations between problem representation and solution. Ill-structured problems can rarely be solved with a single iteration from problem representation to solution generation. Often, challenges and new information surfaced in the solution stage may prompt problem solvers to question their existing problem representation. Consequently, they may revisit the problem representation stage and develop an updated problem representation in light of the new information. However, many learners do not go through the iterative processes. For example, in Huang, Ge et al.'s (2017) study on information problem solving, a learner had only one iteration and one updated problem representation before reaching his final solution. The underlying factors behind the lack of iterations may include immature epistemic beliefs (Huang, Law et al., 2017) or negative emotion (Zhou, 2013a).

Designing Technology-Supported Learning Environments to Support Ill-Structured Problem Solving

Understanding learners' challenges in solving ill-structured problems provides us with a concrete starting point to create a conducive learning environment that leads to productive problem solving. Such learning environments need to be open-ended in supporting learners' goals and means to achieve their goals in problem solving (Hannafin, Land, & Oliver, 1999; Jonassen, 1999). We start by discussing the design of problem scenarios as the first step in building such an environment. We then move on to discuss the design of *hard* scaffolding strategies and tools that can help learners to overcome challenges in ill-structured problem solving.

The Design of Problem Scenarios

Problem scenarios can orient learners to a need or problem and situate them in an interpretive perspective (Hannafin, Land, & Oliver, 1999; Jonassen & Hung, 2008). The scenarios act as the driving force to motivate and engage learners in solving problems. Several dimensions need to be considered in the design of problem scenarios: the complexity of problems, the size of the problem space, level of ill-structuredness or authenticity, and student autonomy. Problems can vary in levels of complexity and student autonomy, providing contexts that range from externally imposed, externally induced, to internally generated, which afford different levels of autonomy to learners (Hannafin et al., 1999). The 3C3R model by Hung (2006) provides guidelines for developing problem scenarios to assure learners' autonomy and cognitive flexibility and to immerse them in scenarios. Problem scenarios should include (1) well aligned and appropriately scoped *content*, (2) valid *context* for the instructional goal and appropriate degree of contextualization, (3) explicit *connections* between the concepts of the domain (Hung, 2006).

A well-designed problem scenario can help to activate learners' schema, which will guide them to identify what is known and unknown, what information is needed, and what skills they need to learn, all of which can prepare learners for problem solving by addressing their challenges in applying prior knowledge and experience. Furthermore, well-designed problem scenarios can afford needed problem space and level of complexity, which can engage learners to self-regulate their cognition and metacognition as they work on problem representation, solution generation, and the navigation between the two stages. Meanwhile, authentic and complex problems can situate learners in appropriate social and cultural contexts, which prompt them to reflect on their epistemological perspectives or stances through constructing arguments and making justifications in the problem-solving processes.

Scaffolding and Tools

Besides providing problem scenarios that orient and engage learners in problem-solving activities, it is also important to design scaffolds and tools to support learners' move from the novice to the expert model. In this section, we use learner challenges as lenses to explore how scaffolds and tools can effectively support ill-structured problem solving.

Scaffold Activation of Prior Knowledge

For learners who do not have sufficient prior knowledge, the 4CID model advocates the provision of just-in-time information (van Merriënboer, Clark, & de Crook, 2002). As learners acquire necessary knowledge in the process, the just-in-time information should be faded away. For students who have difficulty activating prior knowledge pertaining to the current problem, Land (2000) suggested multiple ways to prompt and guide them to see the connection with prior knowledge, including the use of learners' familiar experience, diagrams, or analogies. Technology can provide learners with necessary background information of a problem. For instance, in inquiry-based learning, Reid, Zhang, and Chen (2003) presented learners with multiple-choice questions before the inquiry to activate their prior knowledge in physics in a simulation-based learning environment.

Scaffold Cognitive Processing

Prompts and visualization tools are two ways to scaffold cognitive processing. Prompts can elicit elaboration and explanation of a problem (e.g., Ge & Land, 2003, 2004; Lin, Hmelo, Kinzer, Secules, 1999). Learners can be prompted to articulate problem representations, which makes visible their thinking and help learners to self-regulate themselves. Visualization tools are other means to scaffold cognitive processing (Land, 2000). For example, concept mapping can help learners visualize hard-to-see concepts, which have been used extensively in various learning contexts as conceptual scaffolds to support students' articulation of thoughts. In addition, model-centered learning environments (Seel, 2003) using system dynamic tools have been designed to facilitate meaningful learning in complex problem-solving contexts (Milrad, Spector, & Davidsen, 2003; Shute, Jeong, Spector, Seel, & Johnson, 2009; Spector, Christensen, Sioutine, & McCormack, 2001).

Scaffold Regulative Thinking

Regulative prompts encourage students to reflect on their own learning processes and outcomes (Hannafin, Land, & Oliver, 1999). For instance, Ge and Land (2003) designed metacognitive prompts to guide learners in justifying their solutions and evaluating their problem-solving processes. Lin and Lehman (1999) found that metacognitive prompts helped students to develop an understanding of science inquiry processes. Besides using regulative prompts, instructional designers often use expert modeling to scaffold regulative thinking (Ge, Planas, & Er, 2010; Lajoie & Azevedo, 2000). Expert modeling can trigger learners' reflection by allowing them to see the differences between their own thinking and expert thinking. Technologies can be used to support reflections. For instance, Google Classroom and Flipgrid (asynchronous videos) allow students to journal their reflections and progresses over time. The tools can also help learners to capture how their beliefs and motivation evolve over time during the problem-solving processes.

Scaffold Motivation

Belland, Kim, and Hannafin (2013) proposed a framework to scaffold learner motivation. Drawing from motivation theories, such as goal theories (e.g., Elliott & Dweck, 1988; Miller & Brickman, 2004), expectancy theories (Wigfield & Eccles, 2000), and self-determination theories (Ryan & Deci, 2000), Belland et al. (2013) proposed scaffolds to promote learners' task values, mastery goals, belonging, expectancy, and autonomy. Instructional designers can prompt students to set appropriate short-term and long-term goals (Miller & Brickman, 2004; Quintana, Zhang, & Krajcik, 2005). For instance, Quintana et al. (2005) guide students in setting mastery goals in inquiry learning by using prompts that were open-ended, deep, and interesting. Prompts can also guide students to reflect and articulate the values of their learning outcomes (Kolodner et al., 2003). Besides prompting, expert modeling is often used to illustrate the authentic values of a problem-solving task (e.g., Lajoie & Azevedo, 2000).

Scaffold Epistemic Beliefs

Besides cognitive, metacognitive and motivational functions in a scaffolding system (Narciss, 2008, 2013), learners' epistemic beliefs are an important instructional design consideration in ill-structured problem solving. Epistemic beliefs and self-regulated learning are reciprocal in relationships (Muis, 2007). When a learning environment continuously provides learners the opportunity to purposely examine, monitor, and reflect on their problem representations, solutions, and the alignment between the two, learners are likely to garner feedback from these mental activities, which then feeds into their belief schema. Over time, learners' beliefs will undergo changes, especially when they are prompted to become aware of the changes.

As a belief construct, epistemic beliefs are hard to scaffold through direct interventions. Few studies addressed the relationship between epistemic beliefs and ill-structured problem solving, especially empirical studies. Yet, it does not mean that beliefs cannot be nurtured or enculturated. Self-regulated learning plays a role in the development of epistemic beliefs (Muis, 2007). Indeed, a few studies found that some dimensions of students' epistemic beliefs improved through interventions that emphasized self-regulation and metacognition (Huang, Ge, & Eseryel, 2016; Smith, Maclin, Houghton, & Hennessey, 2000).

Scaffold Navigation Between Problem Representation and Solution Generation

In designing learning environments that help learners to overcome challenges in various aspects of ill-structured problem solving, it is important to understand how various strategies and scaffolds interact and work together to facilitate the whole problem-solving process. The purpose of this chapter is to advocate a holistic approach in designing scaffolds for ill-structured problem solving. An integral aspect of the holistic approach is to help learners navigate between two key problem-solving stages so that solutions can be refined and optimized. In this section, we discuss various scaffolds that help guide learners to navigate between problem-solving stages.

To avoid situations where novice learners misjudge the plausibility of problem representations and leap prematurely to solutions, we can guide them to spend more time and effort on problem representations by prompting them to explore relevant prior knowledge with just-in-time information (van Merriënboer et al., 2002). We can also prompt learners to reflect on the quality of their problem representations (Ge & Land, 2003).

Besides prompting learners to consider the plausibility of problem representations, instructional designers should also prompt students to be mindful of the alignment between their problem representations and solutions. Furthermore, we may prompt learners to articulate how their solutions address the original problem according to their understanding of the problem (Lin et al., 1999). In the articulation process, learners may see the dissonance between their problem representations and solutions, which can subsequently prompt them to revisit their problem representations.

Feedback is another effective strategy to encourage iterative self-regulative thinking. Feedback can take different forms. It can be canned feedback provided by a technology system or adaptive feedback from a face-to-face instructor or other digital channels. In the case of longitudinal problem solving, multiple rounds of feedback can be provided requiring learners to showcase process products or submit progress reports (Huang, Ge et al., 2017).

Facilitating Ill-Structured Problem Solving in Technology-Supported Learning Environments

Expert/Instructor Facilitation

Facilitation is a critical and integral part of dynamic scaffolding, as opposed to the predesigned, hard scaffolding discussed in the previous section (Hmelo-Silver & Barrows, 2006; Jonassen, 1997). Facilitators can be experienced teachers, trainers, or teaching assistants who are trained and skillful in facilitating ill-structured problem solving. Schmidt and Moust (2000) suggest that facilitators should have a "suitable knowledge base regarding the topic under study, a willingness to become involved with students in an authentic way, and the skill to express oneself in a language understood by students" (p. 47). Facilitators can play an essential role in facilitating each process of ill-structured problem solving by adaptively employing strategies and tools to guide learners in achieving problem-solving goals (Hmelo-Silver & Azevedo, 2006).

In the process of facilitation, it is critical that a facilitator understand the individual characteristics learners bring into the learning environment, such as their prior knowledge, motivation, beliefs, emotion, and their zone of proximal development.

Understanding learner characteristics helps a facilitator to pinpoint specific needs and address learning challenges with appropriate strategies and tools. Facilitators should identify who needs support, what kind of support, when to provide support, and how to provide support, based on an understanding of learners' characteristics. In addition, facilitators need to keep in mind the learning goals of problem solving. These learning goals go beyond specific problems to include a broader conceptual space as well as relevant situations, which enable facilitators to provide dynamic scaffolding and address various challenges learners may encounter as they engage in iterative self-regulated problem solving (Barrows, 2000).

Hmelo-Silver and Barrows (2006) found that facilitators scaffold learners' problem solving in both cognitive and sociocultural aspects. Facilitators can scaffold an organized and coherent approach to reasoning and inquiry (Frederiksen, 1999), which can address learners' challenge in cognitive processing and reflective thinking. A facilitator also plays an important role in creating a culture where learners can engage in social discourse on the ill-structured problems to be solved, work together to reach a consensus, validate each other's ideas, and establish norms (Palincsar, 1999). The sociocultural scaffolding can help address issues associated with low motivation and unproductive epistemic beliefs.

Empirical studies provide some insight into effective strategies facilitators can adopt to steer the problem-solving process toward a productive direction (Hmelo-Silver & Barrows, 2006). *Reflective toss* (van Zee & Minstrel, 1997), an effective strategy to scaffold deep thinking in inquiry-based learning, can be used to facilitate ill-structured problem-solving processes. A reflective toss is defined as a particular kind of questioning strategy, which typically consists of a student statement or question, teacher question, and additional student statements, which could carry on in more than one cycle. During this process, the facilitator takes the meaning of a student statement or question and throws the responsibility of elaboration back to the student in a way that influences his/her thinking. van Zee and Minstrel (1997) found that the discourses afforded by reflective tosses help learners to make their meanings clear, consider a variety of perspectives, and monitor their own thinking. Given its cognitive and metacognitive nature, the reflective toss strategy can be used to address a variety of learner challenges in the context of ill-structured problem solving, for example, activating learners' prior knowledge, prompting them to elaborate thoughts and make connections, challenging them to monitor and reflect on their thinking, and encouraging them to articulate underlying beliefs to identify any confusions or misconceptions.

Coaching and modeling (Brown & Campione, 1994; Collins, Brown, & Holum, 1991; Collins, Brown, & Newman, 1989; Jonassen, 1999) through teacher–student *conferencing* can help learners to brainstorm ideas, activate prior knowledge, and represent problems. This strategy helps to address cognitive challenges by helping students develop or execute their problem-solving plans. Feedback from the facilitator can help learners to monitor, evaluate, confirm, or reconsider their plan of actions and move forward in the problem-solving process. This process makes the thinking of both the facilitator and students *visible* (Collins, Brown, & Holum, 1991; Collins, Brown, & Newman, 1989) or *transparent* (Hmelo-Silver & Barrows, 2006).

Expert feedback in written format is another strategy commonly used by facilitators, especially in online problem-based learning. Huang, Ge et al. (2017) found that instructor's feedback served to guide small groups to refocus on the problem under discussion, prompt them to articulate or elaborate their thoughts, clarify misconceptions and issues, and summarize the outcomes of a discussion for further problem solving or decision making. More importantly, the instructor can follow up some valuable discussion threads with further thought-provoking questions, a strategy similar to the previously discussed reflective toss in the classroom setting (Van Zee & Minstrel, 1997). The instructor can also prompt learners to navigate out of an immediate problem space into the larger problem space where they can consider such issues as alignment and coherence. While expert feedback can be a helpful strategy, Huang, Ge et al. (2017) found that students processed the same feedback at different levels, which necessitates additional scaffolding to maximize the benefits of expert feedback. For instance, the instructor could have provided a "revise and resubmit" template and asked the students to describe how they had responded to each feedback and summarized the changes they had made (or not made) based on the feedback. This strategy may help students to process the feedback at a deeper level.

Peer Facilitation

In addition to the facilitation by an expert or instructor, we also need to consider the facilitating role of peers and intentionally promote peer interactions, social discourses, and self-reflections in facilitating ill-structured problem solving (Belland, Glazewski, & Richardson, 2008; Ge & Land, 2003). It is essential that we first examine the affordances of peer facilitation in addressing learner challenges in solving ill-structured problems.

When students are placed in groups, they are given the opportunity to share knowledge and ask questions that elicit explanations from peers, the process of which can help them engage in deeper cognitive processes such as clarifying thinking, reorganizing information, correcting misconceptions, and developing understanding (Webb & Palincsar, 1996). Obviously, peer facilitation may help to address the challenge of cognitive processing. King (1992) argued that the amount of available prior knowledge of any group is larger than that of individuals, which means that the elaboration of the pooled knowledge would lead to a more comprehensive problem representation space than that of an individual problem solver. Empirical evidence supports the role of peer facilitation in building collective knowledge for subsequent problem solving. For instance, Canadian students who had prior experience with online discussions successfully facilitated the students in Hong Kong to complete their collaboration tasks (Lai & Law, 2006). In addition, co-regulation among peers promotes self-regulation of individual students during problem-solving processes (DiDonato, 2013). Successful peer interactions can help learners facilitate each other's problem-solving processes toward productive solutions. This process allows peers to challenge one another's thinking and provides a venue for constructing arguments and making justifications (King, 1992, 1994; King & Rosenshine, 1993). In justifying their solutions or decisions, learners often need to examine and share their underlying beliefs. The peer interaction process also enables learners to see each other's views while interpreting the problem or the solution.

Therefore, peer facilitation can help to address the challenge of lacking prior knowledge in ill-structured problem solving. Furthermore, peers may explain difficult concepts to each other in familiar terms or language understandable to themselves (Brown & Palincsar, 1989). Peers can also direct each other's attention to relevant features and meaningful patterns of the problem. In a technology-supported environment, peer questioning can be effective in facilitating problem-solving processes (Choi, Land, and Turgeon, 2005). By helping learners to co-regulate their problem-solving processes, peer facilitation addresses learner challenges in both cognitive processing and regulative thinking. Peer facilitation can also motivate learners to be more engaged at a deeper level in the problem-solving process while helping them to shape their epistemic beliefs.

However, just as Ge and Land (2003) noticed, students do not necessarily engage automatically or fully in productive peer facilitation. Thus, effective scaffolding strategies and tools are needed to maximize the benefits of peer facilitation. Example of scaffolding strategies or tools for peer facilitation includes providing question prompts or templates (Ge & Land, 2003, 2004). Moreover, learners often need training to become effective and productive facilitators. For example, learners often need help generating higher level, thought-provoking questions in order to stimulate challenging and in-depth problem-solving dialogs. We have seen some teacher professional development on guided inquiry-based learning or problem-based learning, which included asking higher level questions as one of the major components (e.g., Kuhlthau, Maniotes, & Caspari, 2012). This type of professional development can equip teachers or facilitators with useful conceptual tools for facilitating effective peer interactions.

Peer facilitation can be supported with online collaboration platforms such as online discussion boards; yet online discussions need to be structured to be productive. The instructor may provide a structure that requires students to interact with each other by asking elaboration or reflective questions and providing feedback to each other (e.g., Huang, Ge et al., 2017; Law, Ge, & Eseryel, 2011). Furthermore, the written discourses in online discussions make students' thinking transparent, which enable facilitators (both instructor and peers) to understand individuals' epistemic beliefs, clarify misconceptions, and shape beliefs and processes for productive solutions. In recent years, there has been some interest and effort in developing online collaboration and facilitation tools to support ill-structured problem solving for both individuals and groups. HOWARD (Hogaboam et al., 2016) is one such tool that features two components serving two main intentions: (1) a student environment in which students engage in problem-solving activities and (2) an instructor dashboard which condenses and visualizes student activities. HOWARD not only helps students to monitor and facilitate problem-solving discussions but also helps the instructor to evaluate individual and group progress and performance by identifying learner challenges and analyzing regulation patterns in collaborative problem solving.

Tying Together: An Illustration of Holistic Scaffolding

In a college digital media class, students are asked to develop an app with the goal to identify, research, and address certain real-world needs or issues while also gaining valuable knowledge and skills. Undoubtedly, as an ill-structured problem, the app development project presents a variety of challenges for students and their instructor. Both hard and soft scaffolding can be incorporated to guide students' activation of prior knowledge, cognitive processing, regulative thinking, motivation, epistemic beliefs, and the navigation between problem presentation and solution. Hard scaffolding is provided through templates and question prompts delivered through a course management system (CMS, e.g., Canvas) and shared document (e.g., Google document or form, or Google Classroom). Soft scaffolding is provided through the facilitation of an instructor who assumes the role of an expert and peer interactions.

Students' lack of prior knowledge can be addressed by providing just-in-time information in a technology-supported environment. For example, the instructor shows a video that documents the development process of a popular app among the students. The instructor then asks students to research other resources that explain the development process. During this time, the students are provided a template with key elements, such as stakeholders, the objectives and goals of the app, and the system requirements (hard scaffold), and asked to fill out the search information about what they find about the development processes. After that, the instructor asks the students to outline an app development process (e.g., ideation, planning, design, app creation, testing, and launch) using visuals (e.g., a diagram). The instructor uses some examples to illustrate the visual processes to scaffold student thinking. The visual representation of the development process can then serve as a hard cognitive scaffold for the rest of the project.

One of the major tasks of ill-structured problem solving is problem representation. To help address oversimplified problem representations, the instructor can invite students to share their experience as app users (a template can be provided to ensure necessary aspects are covered; for instance, students may consider user interface design, compatibility issues, performance issues, etc.). With peer scaffolding, students may see that app development is driven by user needs, not just to satisfy an instructor.

To help students go beyond their own app experience, the instructor guides them to brainstorm and identify factors and parties involved in the app development (stakeholders, business purpose, system requirements, etc.) in the discussion forum. The instructor also asks students to interview different stakeholders using a predesigned template with guiding questions such as "who are the users and project sponsor of the project" (hard scaffold). Then, the instructor asks the students to share their interviews in the discussion forum or the Google Classroom and leads them in a face-to-face class discussion to compare, contrast, and reflect on how different stakeholders' needs converge or differentiate, especially how the findings differ from their personally perceived needs. The discussion guides students to reflect on their understanding of the problem and the alignment between their problem representation and solution, which the students need to journal according to the weekly reflection template and submit to the online system (Google Classroom or a CMS). Question prompts such as "does my app satisfy the user requirements and business needs?" are provided. As a result, students may update their problem representation as needed. In addition, through the self-regulation process and multiple perspectives that they observe, students' epistemic beliefs may be changed as they see the malleability of knowledge.

To scaffold the solution generation stage, the instructor's feedback as well as resources and tools are provided. The instructor provides iterative feedback to students' project-in-progress in various formats, such as written format delivered to students through the technology platform, or one-to-one, in-class conferencing. In addition, just-in-time information is provided regarding available tools, estimated development time when students have no prior knowledge, etc. When students move too hastily to the design phase (solution) without a clear problem representation, the instructor would question the students' readiness. For example, when students suggest some content to be incorporated in their app, the instructor can ask, "which menu link would this content belong to?" In addition, the instructor provides a checklist (hard scaffold) for the students to perform an initial self-evaluation. This way, students would be prompted to revisit their problem representation to develop a better idea.

While motivation may not be an issue at the beginning, students' motivation often declines and thus needs to be sustained as a project progresses. The instructor may scaffold students to research how applications make an impact on people's lives to reaffirm the values students can make in society. A progress report such as a Gantt chart (hard scaffold) can be an effective motivator that engages students to complete smaller goals, highlights the competence that they developed, and aligns their goals for the project.

Discussion and Conclusion

In this chapter, we have synthesized key ill-structured problem-solving models and presented an updated model that highlights two important characteristics of self-regulated, ill-structured problem solving: its iterative nature and the roles of motivation and beliefs. The existing body of literature mostly focuses on the cognitive and metacognitive dimensions of problem solving (e.g., Ge & Land, 2003; Jonassen, 1997; Sinnott, 1989; Voss & Post, 1988) while leaving out such equally important aspects as motivation, beliefs, and the iterative navigations between problem-solving stages (Ge, Law, & Huang, 2016). Based on the updated model, we have identified major learner challenges and discussed how those challenges can hinder learners' problem-solving processes. Then, we propose designing scaffolding strategies with a holistic perspective to support learners through the self-regulated problem-solving processes informed by the updated model (Ge, Law, & Huang, 2016), with a particular focus on the learner challenges identified earlier. In addition to designing *hard* scaffolds, we also address the design of *soft* scaffolding dynamically provided by instructors and peers (Saye & Brush, 2002). We hope that the challenges and strategies discussed in this chapter can shed light on the effort of instructional designers and classroom instructors in supporting learners' endeavor to solve ill-structured problems.

Although scaffolding strategies and tools have been developed in the last few decades, the effects of scaffolding and tools are mixed (e.g., Belland, Walker, Kim, & Lefler, 2017; Cheung & Slavin, 2013; Reeves & Oh, 2017), which warrants additional research in the field of educational technology. The complex nature of the ill-structured problem-solving process makes the design of scaffolding even more challenging. In designing scaffolding for ill-structured problem solving, we advocate a holistic approach because scaffolding in one area or process may help to scaffold another area or process of problem solving. Furthermore, the complicated problem-solving process often requires more than one scaffolding strategy or tool. Yet, there have been limited inquiries regarding holistic or multiple scaffolds. Future research should continue to explore how to design a holistic scaffolding framework that supports self-regulated, ill-structured problem solving. Another important issue for a technology-supported learning environment for ill-structured problem solving is the assessment of ill-structured problem-solving processes and outcomes. Methodologies, such as "Dynamic Enhanced Evaluation of Problem Solving" (Gogus, Koszalka & Spector, 2009; Spector & Koszalka, 2004), are developed to assess learners' problem representations of ill-structured problems. New techniques such as data mining are used to directly or indirectly assess ill-structured problem-solving (Ifenthaler, 2014; Kim & Clariana, 2017). A comprehensive review of the assessment issues in ill-structured problem-solving is needed for future research in ill-structured problem solving.

References

Barrows, H. S. (2000). *Problem-based learning applied to medical education*. Springfield, IL: Southern Illinois University School of Medicine.

Belland, B., Glazewski, K., & Richardson, J. (2008). A scaffolding framework to support the construction of evidence-based arguments among middle school students. *Educational Technology Research and Development, 56*(4), 401–422. https://doi.org/10.1007/s11423-007-9074-1

Belland, B. R., Kim, C., & Hannafin, M. J. (2013). A framework for designing scaffolds that improve motivation and cognition. *Educational Psychologist, 48*(4), 243–270. https://doi.org/10.1080/00461520.2013.838920

Belland, B. R., Walker, A. E., Kim, N. J., & Lefler, M. (2017). Synthesizing results from empirical research on computer-based scaffolding in stem education: A meta-analysis. *Review of Educational Research, 87*(2), 309–344. https://doi.org/10.3102/0034654316670999

Boekaerts, M. (1997). Self-regulated learning: A new concept embraced by researchers, policy makers, educators, teachers, and students. *Learning and Instruction, 7*(2), 161–186. https://doi.org/10.1016/S0959-4752(96)00015-1

Bransford, J., Brown, A. L., & Cocking, R. (2003). *How people learn: Brain, mind, experience, and school*. Washington, D.C.: National Academy Press.

Brown, A. L., & Palincsar, A. S. (1989). Guided, cooperative learning and individual knowledge acquisition. In L. B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser* (pp. 393–451). Hillsdale, NJ: Lawrence Erlbaum Associates.

Brown, A. L., & Campione, J. C. (1994). Guided discovery in a community of learners. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 229–270). Cambridge, MA: MIT Press.

Bulu, S., & Pedersen, S. (2010). Scaffolding middle school students' content knowledge and ill-structured problem solving in a problem-based hypermedia learning environment. *Educational Technology Research and Development, 58*(5), 507–529. https://doi.org/10.1007/s11423-010-9150-9

Casner-Lotto, J., & Barrington, L. (2006). *Are they really ready to work: Employers perspectives on the knowledge and applied skills of new entrants to the 21st century U.S. workforce*. The Conference Board, Inc., the Partnership for 21st Century Skills, Corporate Voices for Working Families, and the Society for Human Resource Management. Retrieved from http://www.21stcenturyskills.org/index.php?option=com_content&task=view&id=82&Itemid=40

Chen, C.-H. (2010). Promoting college students' knowledge acquisition and ill-structured problem solving: Web-based integration and procedure prompts. *Computers & Education, 55*(1), 292–303. https://doi.org/10.1016/j.compedu.2010.01.015

Cheung, A. C., & Slavin, R. E. (2013). The effectiveness of educational technology applications for enhancing mathematics achievement in k-12 classrooms: A meta-analysis. *Educational Research Review, 9*, 88–113.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research, 63*(1), 1–49. https://doi.org/10.2307/1170558

Choi, I., Land, S. M., & Turgeon, A. (2005). Scaffolding peer-questioning strategies to facilitate metacognition during online small group discussion. *Instructional Science, 33*(5), 483–511. https://doi.org/10.1007/s11251-005-1277-4

Collins, A., Brown, J. S., & Holum, A. (1991). Cognitive apprenticeship: Making thinking visible. *American Educator, 15*(3), 6–11.

Collins, A., Brown, J. S., & Newman, S. E. (1989). Cognitive apprenticeship: Teaching the crafts of reading, writing, and mathematics. In L. B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser* (pp. 453–494). Hillsdale, NJ: Lawrence Erlbaum Associates.

DiDonato, N. (2013). Effective self- and co-regulation in collaborative learning groups: An analysis of how students regulate problem solving of authentic interdisciplinary tasks. *Instructional Science, 41*(1), 25–47. https://doi.org/10.1007/s11251-012-9206-9

Dörner, D. (1987). On the difficulties people have in dealing with complexity. In K. Duncan, J. Rasmussen, & L. Leplat (Eds.), *New technology and human error* (pp. 97–109). Chichester, NY: Wiley & Sons.

Elliott, E. S., & Dweck, C. S. (1988). Goals: An approach to motivation and achievement. *Journal of Personality and Social Psychology, 54*(1), 5–12. https://doi.org/10.1037//0022-3514.54.1.5

Ertmer, P. A., Stepich, D. A., Flanagan, S., Kocaman-Karoglu, A., Reiner, C., Reyes, L.,… Ushigusa, S. (2009). Impact of guidance on the problem-solving efforts of instructional design novices. *Performance Improvement Quarterly, 21*(4), 117–132. https://doi.org/10.1002/piq.20041

Ertmer, P. A., Stepich, D. A., York, C. S., Stickman, A., Wu, X. L., Zurek, S., et al. (2008). How instructional design experts use knowledge and experience to solve ill-structured problems. *Performance Improvement Quarterly, 21*(1), 17–42. https://doi.org/10.1002/piq.20013

Ertmer, P.A., & Stepich, D. (2005). Instructional design expertise: How will we know it when we see it? *Educational Technology, 45*(6), 38–43.

Feltovich, P. J., Spiro, R. J., Coulson, R. L., & Feltovich, J. (1996). Collaboration within and among minds: Mastering complexity, individually and in groups. In T. Koschmann (Ed.), *CSCL: Theory and practice of an emerging paradigm* (pp. 25–44). Mahwah: Lawrence Erlbaum Associates.

Frederiksen, C. H. (1999). Learning to reason through discourse in a problem-based learning group. *Discourse Processes, 27*, 135–160.

Ge, X., Chen, C.-H., & Davis, K. A. (2005). Scaffolding novice instructional designers' problem-solving processes using question prompts in a web-based learning environment. *Journal of Educational Computing Research, 33*(2), 219–248. https://doi.org/10.2190/5F6J-HHVF-2U2B-8T3G

Ge, X., & Chua, B. L. (In Press). Self-directed learning in PBL: The role and skills of learners. In N. Dabbagh, W. Hung, & M. Moallem (Eds.). Wiley handbook of problem-based learning. Wiley

Ge, X., & Hardré, P. (2010). Self-processes and learning environment as influences in the development of expertise in instructional design. *Learning Environments Research, 13*(1), 23–41. https://doi.org/10.1007/s10984-009-9064-9

Ge, X., Huang, K., & Dong, Y. (2010). An investigation of an open-source software development environment in a software engineering graduate course. *Special issue on PBL in Engineering Education, Interdisciplinary Journal of Problem-based Learning, 4*(2), 94–120.

Ge, X., & Land, S. (2003). Scaffolding students' problem-solving processes in an ill-structured task using question prompts and peer interactions. *Educational Technology Research and Development, 51*(1), 21–38. https://doi.org/10.1007/BF02504515

Ge, X., & Land, S. (2004). A conceptual framework for scaffolding ill-structured problem-solving processes using question prompts and peer interactions. *Educational Technology Research and Development, 52*(2), 5–22. https://doi.org/10.1007/BF02504836

Ge, X., Law, V., & Huang, K. (2016). Detangling the interrelationships between self-regulation and ill-structured problem solving in problem-based learning. *Interdisciplinary Journal of Problem-Based Learning, 10*(2), 11. https://doi.org/10.7771/1541-5015.1622

Ge, X., Planas, L., & Er, N. (2010). A cognitive support system to scaffold students' problem-based learning in a web-based learning environment. *Interdisciplinary Journal of Problem-Based Learning, 4*(1), 30–56. https://doi.org/10.7771/1541-5015.1093

Gogus, A., Koszalka, T. A., & Spector, J. M. (2009). Assessing conceptual representations of ill-defined problems. *Technology, Instruction, Cognition and Learning, 7*(1), 1–20.

Hannafin, M. J., Land, S. M., & Oliver, K. (1999). Open learning environments: Foundations, methods, and models. In C. M. Reigeluth (Ed.), *Instructional-design theories and models: A new paradigm of instructional theory* (Vol. 2, pp. 115–140). Mahway, NJ: Lawrence Erlbaum Associates.

Hmelo-Silver, C. E., & Azevedo, R. (2006). Understanding complex systems: Some core challenges. *Journal of the Learning Sciences, 15*(1), 53–61. https://doi.org/10.1207/s15327809jls1501_7

Hmelo-Silver, C. E., & Barrows, H. S. (2006). Goals and strategies of a problem-based learning facilitator. *Interdisciplinary Journal of Problem-Based Learning, 1*(1), 21–39. https://doi.org/10.7771/1541-5015.1004

Hofer, B. K., & Pintrich, P. R. (1997). The development of epistemological theories: Beliefs about knowledge and knowing and their relation to learning. *Review of Educational Research, 67*(1), 88–140. https://doi.org/10.2307/1170620

Hogaboam, P. T., Chen, Y., Hmelo-Silver, C. E., Lajoie, S. P., Bodnar, S., Kazemitabar, M., et al. (2016). Data dashboards to support facilitating online problem-based learning. *Quarterly Review of Distance Education, 17*(3), 75.

Huang, K., Ge, X., & Eseryel, D. (2016). Metaconceptually enhanced simulation-based inquiry: Effects on eighth grade students' conceptual change and science epistemic beliefs. *Educational Technology Research and Development, 65*, 1–26. https://doi.org/10.1007/s11423-016-9462-5

Huang, K., Ge, X., & Law, V. (2017). Deep and surface processing of instructor's feedback in an online course. *Journal of Educational Technology & Society, 20*(4), 247–260.

Huang, K., Law, V., Ge, X., & Yu, C. (2017). The role of epistemic beliefs in the process of solving an information problem. Paper presented at *the Annual Meeting of the American Educational Research Association*, San Antonio, TX.

Hung, W. (2006). The 3C3R model: A conceptual framework for designing problems in PBL. *Interdisciplinary Journal of Problem-based Learning, 1*(1), 55–77. https://doi.org/10.7771/1541-5015.1006

Ifenthaler, D. (2014). Toward automated computer-based visualization and assessment of team-based performance. *Journal of Educational Psychology, 106*(3), 651–665.

Jonassen, D. H. (1997). Instructional design models for well-structured and ill-structured problem-solving learning outcomes. *Educational Technology Research and Development, 45*(1), 65–94. https://doi.org/10.1007/BF02299613

Jonassen, D. H. (1999). Designing constructivist learning environments. In C. M. Reigeluth (Ed.), *Instructional-design theories and models: A new paradigm of instructional theory* (Vol. II, pp. 215–239). Mahway, NJ: Lawrence Erlbaum Associates.

Jonassen, D. H. (2004). *Learning to solve problems: An instructional design guide*. San Francisco: Pfeiffer.

Jonassen, D. H. (2007). What makes scientific problems difficult. In D. Jonassen (Ed.), *Learning to solve complex scientific problems* (pp. 3–23). New York, NY: Lawrence Erlbaum Associates.

Jonassen, D. H., & Hung, W. (2008). All problems are not equal: Implications for PBL. *Interdisciplinary Journal of Problem-Based Learning, 2*(2), 6–28. https://doi.org/10.7771/1541-5015.1080

Kim, K., & Clariana, R. B. (2017). Text signals influence second language expository text comprehension: Knowledge structure analysis. *Educational Technology Research & Development, 65*(4), 909–930.

Kim, M. C., & Hannafin, M. J. (2011). Scaffolding problem solving in technology-enhanced learning environment (teles): Bridging research and theory with practice. *Computers & Education, 56*(2), 403–417. http://dx.doi.org/10.1016/j.compedu.2010.08.024

King, A. (1992). Facilitating elaborative learning through guided student-generated questioning. *Educational Psychologist, 27*(1), 111–126. https://doi.org/10.1207/s15326985ep2701_8

King, A. (1994). Guiding knowledge construction in the classroom: Effects of teaching children how to question and how to explain. *American Educational Research Journal, 31*(2), 338–368. https://doi.org/10.2307/1163313

King, A., & Rosenshine, B. (1993). Effects of guided cooperative questioning on children's knowledge construction. *The Journal of Experimental Education, 61*(2), 127–148. https://doi.org/10.1080/00220973.1993.9943857

Kolodner, J.L., Camp, P.J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., . . . 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. doi: https://doi.org/10.1207/S15327809JLS1204_2

Kuhlthau, C., Maniotes, L., & Caspari, A. (2012). *Guided inquiry design: A framework for inquiry in your school*. Santa Barbara, CA: Libraries Unlimited.

Lai, M., & Law, N. (2006). Peer scaffolding of knowledge building through collaborative groups with differential learning experiences. *Journal of Educational Computing Research, 35*(2), 123–144. https://doi.org/10.2190/GW42-575W-Q301-1765

Lajoie, S. P. (1993). Computer environments as cognitive tools for enhancing learning. In S. P. Lajoie & S. Derry (Eds.), *Computers as cognitive tools* (pp. 261–288). Hillsdale, NJ: Lawrence Erlbaum Associates.

Lajoie, S. P., & Azevedo, R. (2000). Cognitive tools for medical informatics. In S. P. Lajoie (Ed.), *Computers as cognitive tools: Volume ii, no more walls* (pp. 247–273). Mahwah, NJ: Lawrence Erlbaum Associates.

Land, S. (2000). Cognitive requirements for learning with open-ended learning environments. *Educational Technology Research and Development, 48*(3), 61–78. https://doi.org/10.1007/BF02319858

Law, V., Ge, X., & Eseryel, D. (2011). An investigation of the development of a reflective virtual learning community in an ill-structured domain of instructional design. *Knowledge Management & E-Learning: An International Journal, 3*(4), 513–533.

Lin, X., Hmelo, C., Kinzer, C., & Secules, T. (1999). Designing technology to support reflection. *Educational Technology Research and Development, 47*(3), 43–62. https://doi.org/10.1007/BF02299633

Lin, X., & Lehman, J. D. (1999). Supporting learning of variable control in a computer-based biology environment: Effects of prompting college students to reflect on their own thinking. *Journal of Research in Science Teaching, 36*(7), 837–858. https://doi.org/10.1002/(SICI)1098-2736(199909)36:7<837::AID-TEA6>3.0.CO;2-U

Marcus, N., Cooper, M., & Sweller, J. (1996). Understanding instructions. *Journal of Educational Psychology, 88*(1), 49–63.

Milbourne, J., & Wiebe, E. (2017). The role of content knowledge in ill-structured problem solving for high school physics students. *Research in Science Education, 48*, 165. https://doi.org/10.1007/s11165-016-9564-4

Miller, R., & Brickman, S. (2004). A model of future-oriented motivation and self-regulation. *Educational Psychology Review, 16*(1), 9–33. https://doi.org/10.1023/B:EDPR.0000012343.96370.39

Milrad, M., Spector, J. M., & Davidsen, P. I. (2003). Model facilitated learning. In S. Naidu (Ed.), *Learning and teaching with technology: Principles and practices* (pp. 13–27). London, UK: Kogan Page.

Muis, K. R. (2007). The role of epistemic beliefs in self-regulated learning. *Educational Psychologist, 42*(3), 173–190.

Narciss, S. (2008). Feedback strategies for interactive learning tasks. In J. M. Spector, M. D. Merrill, J. van Merrienboer, & M. Driscoll (Eds.), *Handbook of research on educational communications and technology* (Vol. 3, pp. 125–144). Mahwah, NJ: Routledge.

Narciss, S. (2013). Designing and evaluating tutoring feedback strategies for digital learning environments on the basis of the interactive tutoring feedback model. *Digital Education Review, 12*, 7–26.

Palincsar, A. S. (1999). Applying a sociocultural lens to the work of a transition community. *Discourse Processes, 27*, 161–171.

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 63*(2), 167–199. https://doi.org/10.3102/00346543063002167

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.

Quintana, C., Zhang, M., & Krajcik, J. (2005). A framework for supporting metacognitive aspects of online inquiry through software-based scaffolding. *Educational Psychologist, 40*(4), 235–244. https://doi.org/10.1207/s15326985ep4004_5

Reeves, T. C., & Oh, E. G. (2017). The goals and methods of educational technology research over a quarter century (1989–2014). *Educational Technology Research and Development, 65*(2), 325–339. https://doi.org/10.1007/s11423-016-9474-1

Reid, D. J., Zhang, J., & Chen, Q. (2003). Supporting scientific discovery learning in a simulation environment. *Journal of Computer Assisted Learning, 19*(1), 9–20. https://doi.org/10.1046/j.0266-4909.2003.00002.x

Robertson, S. I. (2017). *Problem solving: Perspectives from cognition and neuroscience* (2nd ed.). New York: Routledge.

Rumelhart, D. E., & Norman, D. A. (Eds.). (1978). *Accretion, tuning and restructuring: Three modes of learning*. Hillsdale, NJ: Erlbaum.

Ryan, R., & Deci, E. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist, 55*(1), 68–78.

Saye, J., & Brush, T. (2002). Scaffolding critical reasoning about history and social issues in multimedia-supported learning environments. *Educational Technology Research and Development, 50*(3), 77–96. https://doi.org/10.1007/BF02505026

Schmidt, H. G., & Moust, J. H. C. (2000). Factors affecting small-group learning: A review of the research. In C. E. Hmelo (Ed.), *Problem-based learning: A research perspective on learning interactions* (pp. 19–52). Mahwah, NJ: Erlbaum.

Schraw, G., Dunkle, M. E., & Bendixen, L. D. (1995). Cognitive processes in well-defined and ill-defined problem solving. *Applied Cognitive Psychology, 9*, 523–538.

Seel, N. M. (2003). Model-centered learning environments. *Technology, Instruction, Cognition, and Learning, 1*(3), 242–251.

Shin, N., Jonassen, D. H., & McGee, S. (2003). Predictors of well-structured and ill-structured problem solving in an astronomy simulation. *Journal of Research in Science Teaching, 40*(1), 6–33. https://doi.org/10.1002/tea.10058

Shute, V., & Psotka, J. (1996). Intelligent tutoring systems: Past, present, and future. In D. H. Jonassen (Ed.), *Handbook of research for educational communications and technology* (Vol. 1, pp. 570–600). Macmillan Library Reference.

Shute, V. J., Jeong, A. C., Spector, J. M., Seel, N. M., & Johnson, T. E. (2009). Model-based methods for assessment, learning, and instruction: Innovative educational technology at Florida State University. In M. Orey (Ed.), *2009 educational media and technology yearbook* (pp. 61–80). Westport, CT: Greenwood Publishing Group.

Sinnott, J. D. (1989). A model for solution of ill-structured problems: Implications for everyday and abstract problem solving. In J. D. Sinnott (Ed.), *Everyday problem solving: Theory and application* (pp. 72–99). New York: Praeger.

Smith, C., Maclin, D., Houghton, C., & Hennessey, G. (2000). Sixth-grade students' epistemologies of science: The impact of school science experiences on epistemological development. *Cognition and Instruction, 18*(3), 349–422.

Spector, J. M., Christensen, D. L., Sioutine, A. V., & McCormack, D. (2001). Models and simulations for learning in complex domains: Using causal loop diagrams for assessment and evaluation. *Computers in Human Behavior, 17*(5–6), 517–545.

Spector, J. M., & Koszalka, T. A. (2004). *The DEEP methodology for assessing learning in complex domains (final report to the National Science Foundation evaluative research and evaluation capacity building)*. Syracuse, NY: Syracuse University.

van Merriënboer, J. J. G., Clark, R., & de Croock, M. (2002). Blueprints for complex learning: The 4c/id-model. *Educational Technology Research and Development, 50*(2), 39–61.

van Zee, E., & Minstrell, J. (1997). Using questioning to guide student thinking. *Journal of the Learning Sciences, 6*(2), 227.

Voss, J. F., & Post, T. A. (1988). On the solving of ill-structured problems. In M. T. H. Chi & R. Glaser (Eds.), *The nature of expertise* (pp. 261–285). Hillsdale, NJ: Lawrence Erlbaum Associates.

Wallace, R. M., Kupperman, J., Krajcik, J., & Soloway, E. (2000). Science on the web: Students online in a sixth-grade classroom. *Journal of the Learning Sciences, 9*(1), 75–104. https://doi.org/10.1207/s15327809jls0901_5

Webb, N. M., & Palincsar, A. S. (1996). Group process in the classroom. In D. C. Berliner & R. C. Calfee (Eds.), *Handbook of educational psychology* (pp. 841–876). New York: Macmillan.

Wigfield, A., & Eccles, J. S. (2000). Expectancy–value theory of achievement motivation. *Contemporary Educational Psychology, 25*(1), 68–81. https://doi.org/10.1006/ceps.1999.1015

Zhou, M. (2013a). "I am really good at it" or "I am just feeling lucky": The effects of emotions on information problem-solving. *Educational Technology Research & Development, 61*, 505–520.

Zhou, M. (2013b). Using traces to investigate self-regulatory activities: A study of self-regulation and achievement goal profiles in the context of web search for academic tasks. *Journal of Cognitive Education & Psychology, 12*(3), 287–305. https://doi.org/10.1891/1945-8959.12.3.287