Chapter 1
Introduction

Abstract In this chapter, I describe the call for the use of problem-centered instructional approaches in science, technology, engineering, and mathematics (STEM) education. I note the rationale for this book—specifically that it allows me space to explain the theoretical background of scaffolding and to explore the theoretical implications of a meta-analysis of computer-based scaffolding in STEM education that I completed with colleagues. I also posit instructional scaffolding as an intervention that extends students' capabilities as they engage with the central problem in problem-centered instructional approaches. I note the difference between one-to-one, peer, and computer-based scaffolding, and articulate that in this book I synthesize research on computer-based scaffolding in STEM education. Finally, I outline the structure of the book.

Keywords Computer-based scaffolding · Meta-analysis · Problem-centered instruction · Scaffolding · STEM education

1.1 Why Write a Book on Computer-Based Scaffolding in STEM Education?

In the most widely read and highly cited article of *Educational Psychologist*, Kirschner, Sweller, and Clark (2006) argued that problem-centered instructional approaches were ineffective due to their purported incorporation of minimal guidance. There is some truth in the argument of Kirschner et al. (2006), in that problem-centered instructional approaches that include *no* student guidance lead to weaker learning outcomes compared to direct instruction (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Hung, 2011). However, problem-centered models of instruction do incorporate strong support for student learning in the form of instructional scaffolding (Hmelo-Silver, Duncan, & Chinn, 2007; Schmidt, van der Molen, te Winkel, & Wijnen, 2009). Furthermore, asking if problem-centered instruction or lecture is more effective is not asking a productive question; rather, it is crucial to consider effectiveness using the metric of the learning goals one is trying to promote among students (Hmelo-Silver et al., 2007; Kuhn, 2007). Compared to that of lecture, the influence of problem-centered instruction paired with appropriate student support

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on student learning is stronger in terms of the principles that connect concepts and application of learned content to new problems (Gijbels, Dochy, Van den Bossche, & Segers, 2005; Schmidt et al., 2009; Strobel & van Barneveld, 2009; Walker & Leary, 2009) and long-term retention of knowledge (Dochy, Segers, Van den Bossche, & Gijbels, 2003; Kuhn, 2007; Strobel & van Barneveld, 2009). That problem-centered instruction fares well when it comes to deep content learning and principles and application outcomes is well-established. But the effectiveness of various computer-based scaffolding strategies is less well understood. That is the need that this book, and the underlying meta-analysis project, sought to address.

While meta-analyses and meta-syntheses have established convincing evidence bases in support of the effectiveness of problem-centered instructional models, such syntheses of empirical research on instructional scaffolding are an emergent phenomenon (Belland, Walker, Kim, & Lefler, 2014; Belland, Walker, Olsen, & Leary, 2015; Swanson & Deshler, 2003; Swanson & Lussier, 2001). Existing meta-analyses are either small-scale, or only focus on one subtype of computer-based scaffolding. For example, one such meta-analysis focuses on dynamic assessment (Swanson & Lussier, 2001). In another, included studies were referrals from a narrative review of studies on computer-based scaffolding (Belland, Walker, et al., 2015).

Instructional scaffolding is an essential tool to support students during problem-centered instruction (Belland, Glazewski, & Richardson, 2008; Lu, Lajoie, & Wiseman, 2010; Reiser, 2004; Schmidt, Rotgans, & Yew, 2011). It makes sense to pursue synthesis of empirical research on computer-based scaffolding further so as to not “know less than we have proven,” which is often the risk that is run when accumulating hundreds of empirical studies on a topic (Glass, 1976, p. 8).

The use of computer-based scaffolding paired with problem-centered instruction has emerged as a common and valued approach in science education (Crippen & Archambault, 2012; Lin et al., 2012), engineering education (Bamberger & Cahill, 2013; Gómez Puente, Eijck, & Jochems, 2013), and mathematics education (Aleven & Koedinger, 2002). To fully understand how to support students effectively in problem-centered instructional approaches, it is necessary to know the most promising strategies for instructional scaffolding (Belland et al., 2008; Lin et al., 2012; Quintana et al., 2004). The underlying base of empirical research on instructional scaffolding is undeniably large (Koedinger & Corbett, 2006; Lin et al., 2012), which makes it reasonable to synthesize the research using the tools of meta-analysis. In this way, one can determine which scaffolding characteristics and contexts of use have the biggest influence on learning outcomes. This book explores the role of instructional scaffolding in supporting students engaged in problem-centered instructional models in science, technology, engineering, and mathematics (STEM) education. It grew out of a project in which colleagues and I conducted a meta-analysis of research on computer-based scaffolding in STEM education. As a preview, computer-based scaffolding led to a statistically significant and substantial effect of $g = 0.46$ on cognitive outcomes (Belland, Walker, Kim, & Lefler, In Press).

For many meta-analysts, reading the journal article in which my colleagues and I reported our meta-analysis is enough as it reports methodology, coding process, tests for heterogeneity, inter-rater reliability, and other important meta-analysis details (Belland et al., In Press). However, as any researcher knows, the amount of theoretical background and practical details that one can fit into one journal paper is often woefully inadequate as there simply is not enough space. Writing a book allows one to have adequate space for important theoretical background and practical details. Thus, scaffolding designers and STEM education researchers and instructors may find this book to be particularly useful as they consider how to design scaffolding and the nature of coding categories used in the meta-analysis. Meta-analysts may also find the book to be useful as they consider how coding categories were defined in the underlying meta-analysis.

1.2 What This Book Covers

This book focuses on computer-based scaffolding in STEM education—its definition and theoretical backing, how it has been applied in STEM education, evidence of its effectiveness, under what conditions computer-based scaffolding is most effective, and which scaffolding characteristics lead to the strongest cognitive outcomes. The use of computer-based scaffolding paired with problem-centered instruction is neither new to nor limited to STEM education (Belland, 2014; Brush & Saye, 2001; Hawkins & Pea, 1987; Rienties et al., 2012). Furthermore, researchers have found evidence of strong learning outcomes from the combination not only in STEM education but also in such subjects as social studies (Nussbaum, 2002; Saye & Brush, 2002), economics (Rienties et al., 2012), and English education (Lai & Calandra, 2010; Proctor, Dalton, & Grisham, 2007).

While the underlying meta-analysis did not include studies from outside of STEM education, there is material in this book that is pertinent to scaffolding in education areas other than STEM. These include the conditions under which scaffolding is used and the characteristics often present in scaffolding. However, findings about conditions under which scaffolding is most effective, student populations among whom scaffolding is used, and which scaffolding characteristics lead to the strongest impact on cognitive outcomes may not apply in non-STEM education settings. Further research is needed to ascertain this. Where the material is not directly applicable, it may suggest avenues for future research to better understand the role of computer-based scaffolding in education in the humanities and social sciences. Such future research is every bit as important as research on scaffolding in STEM education to the preparation of a well-rounded citizenry who is capable of thinking critically and creatively about problems (Guyotte, Sochacka, Costantino, Walther, & Kellam, 2014; Stearns, 1994).

1.3 Problem-Centered Instructional Approaches and STEM

Problem-centered approaches have been growing in importance in STEM education (Abd-El-Khalick et al., 2004; Carr, Bennett, & Strobel, 2012; Duschl, 2008; National Research Council, 2012). Such approaches can vary widely in terms of processes students and teachers follow and goals students pursue (Savery, 2006). For example, in terms of goals, in project-based learning and design-based learning, students are presented with the challenge of designing a product that addresses a problem (Doppelt, Mehalik, Schunn, Silk, & Krysinski, 2008; Kolodner et al., 2003; Krajcik et al., 1998). Design-based learning usually integrates science content with a focus on engineering design, and students need to follow an engineering design process to conceive of and build the product (Kolodner et al., 2003; Silk, Schunn, & Cary, 2009). In project-based learning, design is not tied to a particular discipline (Barron et al., 1998; Krajcik, McNeill, & Reiser, 2008). In problem-based learning, students need to determine a conceptual solution to an ill-structured problem and defend it with appropriate argumentation (Barrows & Tamblyn, 1980; Belland et al., 2008; Hmelo-Silver, 2004).

Processes used in problem-centered instructional approaches can range from studying similar cases to extract solution principles and to subsequently adapt such to address the present problem (case-based learning; see Kolodner, Owensby, & Guzdial, 2004; Srinivasan, Wilkes, Stevenson, Nguyen, & Slavin, 2007) to examining a simulated patient, determining and addressing learning issues, and creating and defending a diagnosis (problem-based learning; see Barrows, 1985; Hmelo et al., 2001). While there are certainly variations in processes and goals of problem-centered approaches, a commonality is that at all of their cores are ill-structured problems (Jonassen, 2011; Savery, 2006). Ill-structured problems are problems for which there are more than one possible solution and many acceptable solution paths (Jonassen, 2000, 2011). They are the types of problems that professionals get paid to solve, and yet such problems are rarely included in K-12 curricula (Giere, 1990; Jonassen, 2011; Nersessian, 2008). Determining how to support students most effectively during this important process has the potential to improve education's capacity to prepare students to be successful in the twenty-first-century economy (Casner-Lotto & Barrington, 2006; Gu & Belland, 2015).

As one might guess, addressing ill-structured problems is not easy. For everyone except perhaps the most advanced experts, addressing ill-structured problems requires the use of unfamiliar strategies and the learning and subsequent use of much content knowledge (Giere, 1990; Jonassen, 2011; Nersessian, 2008). However, success at addressing authentic ill-structured problems in school is possible if students are provided appropriate instructional scaffolding to extend and enhance their capabilities as they engage with the target problems (Belland, 2010; Belland, Gu, Armbrust, & Cook, 2015; Hmelo-Silver et al., 2007).

1.4 Role of Scaffolding

When considering problem-centered approaches to instruction, a central question has been how one can provide the support that students need to succeed in this environment. One cannot expect to teach students all of the strategies and content that they need through lecture or other approaches ahead of students' engagement with the central problem (Barrows & Tamblyn, 1980; Hmelo-Silver, 2004). Rather, support provided to students engaging in problem-centered instructional approaches needs to incorporate scaffolding, defined as interactive support that leverages what students already know to help them meaningfully participate in and gain skill at tasks that are beyond their unassisted abilities (Belland, 2014; Hmelo-Silver et al., 2007; Schmidt et al., 2011; van de Pol, Volman, & Beishuizen, 2010; Wood, Bruner, & Ross, 1976). Such support leverages what students can already do to help them accomplish things that they would not be able to do otherwise, such as solve the central problem, design an artifact to address the problem, or complete a project (See Fig. 1.1). Scaffolding can be provided by teachers, peers, or computer tools (Belland, 2014; Pifarre & Cobos, 2010; van de Pol et al., 2010), but implementing problem-centered instruction in K-12 settings requires the use of computer-based scaffolding due to the high student-to-teacher ratios in most K-12 schools (Crippen & Archambault, 2012; Saye & Brush, 2002).

Instructional scaffolding differs from other instructional support strategies and tools in terms of what students are intended to get out of it, the timing of the support, and the form of the support. First, scaffolding needs to support current performance but also lead to the ability to perform the target skill independently in the future (Belland, 2014; Wood et al., 1976). Thus, a calculator does not qualify as a scaffold because while it supports current performance, it cannot be reasonably expected to help users calculate independently (i.e., without the use of a calculator) more effectively in the future. Second, scaffolding is used while students engage with an authentic/ill-structured problem (Belland, 2014; Collins, Brown, & Newman, 1989; Wood et al., 1976). Modeling a strategy, lecturing to students, or otherwise instructing about strategies or content before engagement with problems does not qualify as scaffolding. Third, scaffolding needs to (a) build off of what students already know and (b) be tied to ongoing assessment of

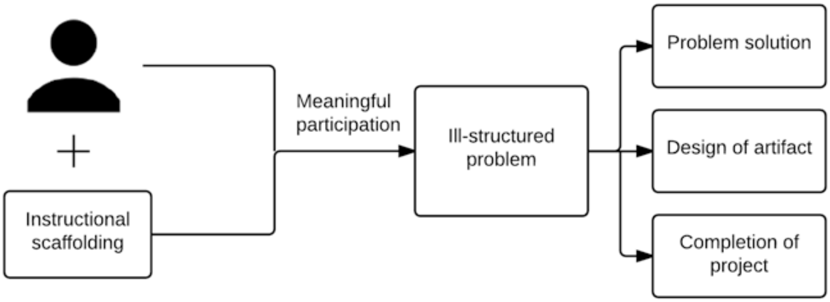

Fig. 1.1 The role of instructional scaffolding in solving ill-structured problems

student abilities (Graesser, Bowers, Hacker, & Person, 1997; van de Pol et al., 2010; Wood et al., 1976). Thus, simply telling students what to do or how to do it does not qualify as scaffolding, because the former approach does not elicit and build off of what students already know. Such an approach is not often tailored to students' individual needs. Fourth, scaffolding needs to simplify some task elements but also retain and highlight the complexity of other task elements (Reiser, 2004; Simons & Ertmer, 2006). This is so as to make meaningful participation in the task possible, but also to focus student attention on the subsets of the problem that will lead to the desired learning and promote the type of productive struggle that is the highlight of effective scaffolding interventions (Belland, Glazewski, & Richardson, 2011; Reiser, 2004; Simons & Ertmer, 2006). Without such struggle, productive learning from scaffolding cannot happen.

Scaffolding can be provided by teachers, computers, or peers (Belland, 2014; Hawkins & Pea, 1987; Hogan & Pressley, 1997; Lutz, Guthrie, & Davis, 2006; Pifarre & Cobos, 2010; van de Pol et al., 2010). Each of these scaffolding types form an important part of an overall scaffolding system (Belland, Gu, Armbrust, & Cook, 2013; Helle, Tynjälä, & Olkinuora, 2006; Puntambekar & Kolodner, 2005; Saye & Brush, 2002). That is, the relative strengths and weaknesses of each can compensate for that of the others, forming a strong network of instructional support for students.

1.5 Central Premises Behind This Book

A central argument of this book is that a systematic synthesis of research on computer-based scaffolding across STEM education is warranted so as to allow researchers and instructors in different disciplines to benefit from research done in other fields. Three premises of the argument are (a) that it does not make sense to continually create from scratch scaffolding strategies when endeavoring to support students in new situations, (b) there is far too much empirical work on scaffolding in STEM fields to make sense of what works best in what circumstances without the use of meta-analysis or other comprehensive synthesis methods (e.g., meta-synthesis), and (c) it makes sense to synthesize research on scaffolding based in different theoretical traditions and used in the context of diverse instructional approaches. I discuss and support these premises in the paragraphs that follow.

Premise (a)—that it does not make sense to continually create from scratch scaffolding strategies when endeavoring to support students in new situations—is supported by needs for the creation of tools and strategies for supporting student learning in a manner that builds off of prior research and development (Boote & Beile, 2005; Edelson, 2002; Institute of Education Sciences, U.S. Department of Education, & National Science Foundation, 2013; Wang & Hannafin, 2005). The act of design, and the collection of data about how it works in authentic contexts, is certainly an important contributor to the base of knowledge in a research area (Brown, 1992; Edelson, 2002; Wang & Hannafin, 2005). Still, there is much published research on the effectiveness of various scaffolding strategies, and it is important that such research inform future development efforts. By engaging in a broad synthesis of scaffolding research, one can synthesize lessons learned in diverse studies in order to form an understanding of what works in scaffolding (Borenstein, Hedges, Higgins, & Rothstein, 2009; Cooper, Hedges, & Valentine, 2009). Specifically, it can help one to obtain a relatively accurate estimate of the magnitude of the difference in cognitive learning outcomes between control students and students who use scaffolding that (a) is designed to promote particular learning outcomes, (b) incorporates particular features, or (c) is used in particular contexts. This can then allow scaffolding designers to implement the most promising scaffolding features in the most promising contexts.

For premise (b)—there is far too much empirical work on scaffolding in STEM fields to make sense of what works best in what circumstances without the use of meta-analysis or other comprehensive synthesis methods—the final traditional meta-analysis included 333 outcomes from 144 studies on computer-based scaffolding in STEM education (Belland, Walker, Kim, & Lefler, In Press). Of note, multiple outcomes from the same study were maintained as separate outcomes when they were associated with differences in coded scaffolding or outcome characteristics. These studies are the ones that met our inclusion criteria and emerged from a much larger corpus of studies. Notably, included studies needed to have (a) a treatment and a control group, (b) an intervention that qualified as computer-based scaffolding, (c) sufficient information to calculate an effect size, and (d) cognitive learning outcomes. Synthesizing such a large number of research studies without the use of a systematic synthesis method would be difficult indeed. As a systematic synthesis method, meta-analysis can bring order to such a synthesis and lead to the generation of useful summary statistics.

Our finding of 333 outcomes from 144 studies represents only some of the empirical research on computer-based scaffolding, as there is much research on computer-based scaffolding that does not include a control group or is qualitative, and there are many studies that do not include enough information to calculate an effect size. Rather than contact the authors for more information, the latter studies were excluded due to a decision that it was best to only use information included in research reports in our coding. Other reasons for exclusion included that two or more papers reported results from the same dataset. In that case, the paper with the most detail (e.g., dissertation) was included, while the paper with the least detail (e.g., conference proceeding or journal article) was excluded. In short, some excluded studies involved interventions that met the computer-based scaffolding definition, but were excluded based on failure to meet other inclusion criteria. Thus, the total number of empirical studies on scaffolding in STEM education is considerably higher than the total number of studies included in the meta-analysis.

Premise (c)—it makes sense to synthesize research on scaffolding grounded in different theoretical traditions and used in the context of diverse instructional approaches—is supported by the fact that we applied a strict definition of scaffolding that focused on its use to extend student reasoning abilities while addressing an authentic, ill-structured problem. Thus, if the intervention in question did not fit that definition (e.g., was not used to extend student capabilities as they addressed authentic problems), it was excluded. This means that the scaffolding interventions that were included in the meta-analysis were largely similar in terms of inherent goals of the intervention. Next, we employed a random effects model for analysis, which does not assume homogeneity of studies, and allows one to make inferences beyond the set of studies included in the meta-analysis (Cafri, Kromrey, & Brannick, 2010; Hedges & Vevea, 1998). Furthermore, we coded for characteristics on which scaffolding informed by the different theoretical traditions vary, such as intended learning outcome, scaffolding customization presence, and the basis of scaffolding customization. In this way, we could test empirically if these characteristics influence cognitive outcomes. Next, while there is much variation in the processes of various problem-centered instructional approaches, to be included in this meta-analysis, students needed to address an authentic/ill-structured problem. Thus, if the central problem had one right solution, one right way to arrive at the solution, or did not relate to students' lives, the article was excluded.

In this book, I do not discuss extensively one-to-one or peer scaffolding, as that would be outside the scope. However, these scaffolding strategies are important elements of a comprehensive scaffolding strategy, as each has a different set of attributes that allow each scaffolding type to complement each other (Belland, 2014; Belland, Burdo, & Gu, 2015; Belland et al., 2013; Puntambekar & Kolodner, 2005; Puntambekar, Stylianou, & Goldstein, 2007; Saye & Brush, 2002). Readers who are interested in learning more about peer scaffolding are directed to Pata, Lehtinen, and Sarapuu (2006), Pifarre and Cobos (2010), Sabet, Tahriri, and Pasand (2013), and Yarrow and Topping (2001), and readers interested in learning more about one-to-one (teacher) scaffolding are directed to Belland, Burdo et al. (2015), Chi (1996), Jadallah et al. (2010), van de Pol et al. (2010), and Wood (2003). At a minimum, it is crucial to consider one-to-one scaffolding alongside computer-based scaffolding, as computer-based scaffolding by itself would be ineffective (McNeill & Krajcik, 2009; Muukkonen, Lakkala, & Hakkarainen, 2005; Saye & Brush, 2002). This is in part due to a teacher's ability to question student understanding and dynamically adjust support in a highly effective manner (Rasku-Puttonen, Eteläpelto, Häkkinen, & Arvaja, 2002; van de Pol, Volman, Oort, & Beishuizen, 2014), often in a far more effective manner than any computer-based tool can (Muukkonen et al., 2005; Saye & Brush, 2002).

1.6 Structure of the Book

This book was written with funding from a National Science Foundation grant project (award # 1251782) in which the current author and colleagues conducted a meta-analysis of computer-based scaffolding in STEM education. The goal in the project was to find out which scaffolding strategies lead to the strongest cognitive outcomes, and under what circumstances. The goal of this book is to communicate the theoretical background and findings of the project in a more descriptive fashion than a journal article format would allow. The intent is that readers gain an in-depth understanding of the historical and theoretical foundations of scaffolding and problem-centered approaches to instruction, learn how scaffolding is applied and in what contexts, and see what scaffolding strategies have been the most effective and why. It is important to note that I see this book as only the start of a conversation on the effectiveness of scaffolding strategies in STEM education, as meta-analysis can include only certain quantitative studies and does not account for the many qualitative studies of scaffolding in STEM (Cooper et al., 2009; Sutton, 2009), including much of what emerges from design-based research approaches (Anderson & Shattuck, 2012; Brown, 1992; Wang & Hannafin, 2005). All empirical studies on computer-based scaffolding are important contributions to an understanding of the instructional approach, and so studies that were not included in the meta-analysis as well as new studies that emerge should be considered alongside project findings. Such consideration of other studies may lead to different conclusions about what makes scaffolding effective or not effective. Nonetheless, it is important to systematically synthesize eligible quantitative research first, such that important trends can be identified and pursued further. Otherwise, one runs the risk of designing scaffolding based on an incomplete understanding of the most effective scaffolding strategies.

The rest of the book proceeds as follows. In Chap. 2, I discuss the original and evolving definition of instructional scaffolding as well as the different theoretical bases that inform this evolution. Differences in the operationalization of the term *scaffolding* according to different theoretical bases are explored. This is supported by the idea that it is important to know how the definition of instructional scaffolding has expanded as its delivery mechanisms and the situations in which it is used have expanded. It is also crucial to understand what I mean when I use the term *scaffolding*, as the term means many things to many people (Palincsar, 1998; Pea, 2004; Puntambekar & Hübscher, 2005).

In Chap. 3, I discuss the contexts in which computer-based scaffolding is used, including grade level (e.g., elementary school, graduate school), learner population characteristics (e.g., low-SES, traditional, under-represented), subject (e.g., science, technology), and problem-centered model with which scaffolding is used (e.g., problem-based learning, case-based learning). The wide range of contexts of use of scaffolding is important to consider as one thinks about how to apply the scaffolding metaphor in education and how scaffolding's effectiveness varies according to the context in which it is used (Stone, 1998). Such wide variation in contexts of use can be seen to correspond with wide variations in scaffolding strategies.

In Chap. 4, I discuss the intended learning outcomes of scaffolding as well as assessment strategies used to measure student learning from scaffolding. I also note alignment of the intended learning outcomes and assessment approaches with goals of STEM education as outlined in the Next Generation Science Standards. This is important, as instructional scaffolding has evolved to support students' performance and learning of diverse skills (Puntambekar & Hübscher, 2005). Given such an expansion, it is important to see if scaffolding leads to different impacts according to the varied intended learning outcomes.

In Chap. 5, I describe variations in scaffolding strategy, including scaffolding function (e.g., conceptual, metacognitive), context-specificity (i.e., context-specific or generic), customization (e.g., fading, adding), and customization schedule (e.g., performance-based, fixed). These variations relate to some of the persistent debates in the scaffolding literature (Belland, 2011; Hannafin, Land, & Oliver, 1999; McNeill & Krajcik, 2009; McNeill, Lizotte, Krajcik, & Marx, 2006; Pea, 2004; Puntambekar & Hübscher, 2005). It is important to see if such variations in scaffolding strategy lead to differences in cognitive outcomes.

I also note variations in effect size estimates according to the characteristics covered in Chaps. 3–5. Notably, many of the details related to the methodology used in the underlying meta-analysis are not presented in this book. Interested readers should refer to Belland et al. (In Press).

Finally, in Chap. 6, I conclude the book, noting lessons learned about scaffolding in STEM education and proposing directions for future research.

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