Brian R. Belland

Instructional Scaffolding in STEM Education

Strategies and Efficacy Evidence

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Contents

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

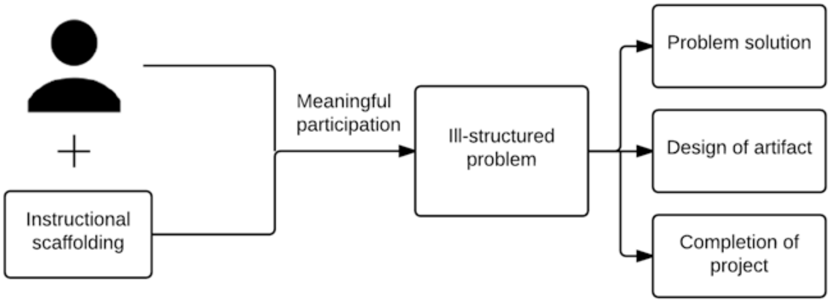

Fig. 1.1 The role of instructional scaffolding in solving ill-structured problems

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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Chapter 2
Instructional Scaffolding: Foundations and Evolving Definition

Abstract This chapter covers the definition of instructional scaffolding, as well as its theoretical bases, and how those bases are reflected in computer-based scaffolding. Computer-based scaffolding is defined as a computer-based tool that extends and enhances student capabilities as students engage with authentic and ill-structured tasks. Despite its original atheoretical nature, scaffolding was linked to many theoretical frameworks, including activity theory, Adaptive Character of Thought-Rational (ACT-R), and knowledge integration. This variation in theoretical frameworks has led to differing scaffolding strategies (e.g., fading, adding, and fading/adding strategies) and overall scaffolding approaches. These are described in depth in this chapter.

Keywords Activity theory · ACT-R · Adding · Computer-based scaffolding · Contingency · Design of scaffolding · Dynamic assessment · Fading · Fading/adding · Intelligent tutoring systems · Intersubjectivity · Knowledge integration · One-to-one scaffolding · Peer scaffolding

2.1 Historical Definition

The metaphor of instructional scaffolding was originally proposed to describe how parents and teachers provided dynamic support to toddlers as they learned to construct pyramids with wooden blocks (Wood, Bruner, & Ross, 1976). This support was meant to extend students' current abilities, meaning that even while supported, toddlers did the bulk of the work required to solve the problem. Scaffolding thus helped fill in key gaps in students' abilities and knowledge such that they could then complete the task. In so doing, it simplified some task elements that were not central to learning to perform the skill independently, but also helped draw students' attention to particularly important task elements, ensuring that these elements were not simplified (Reiser, 2004). It also helped to enlist students' interest in the learning task and sustain their engagement (Belland, Kim, & Hannafin, 2013). Scaffolding was meant to support toddlers temporarily as they engaged with problems, but also to lead to skill gain to enable independent problem-solving in the future (Collins, Brown, & Newman, 1989; Wood et al., 1976).

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Scaffolding was contingent, meaning that scaffolding encompassed two key events that were at once iterative and interconnected—dynamic assessment of the child's current performance characteristics and provision of just the right support (Collins et al., 1989; Tzuriel, 2000; van de Pol, Volman, & Beishuizen, 2011; Wood, 2003). That is, determination of just the right support to be provided to students was always based on dynamic assessment. As dynamic assessment indicated that students were gaining skill and were on the path to being able to perform the task independently, support could be reduced (faded; Collins et al., 1989; Pea, 2004; Wood et al., 1976). If dynamic assessment indicated that students were struggling to participate meaningfully, support could be increased (added; Anderson, Matessa, & Lebiere, 1997; Koedinger & Aleven, 2007).

Scaffolding also required intersubjectivity—an understanding of what successful performance of the target task would look like that was shared between the scaffolder and the scaffoldee (Wertsch & Kazak, 2005; Wood et al., 1976). This was considered necessary so that the students would themselves know when the task had been accomplished successfully, which is crucial to independent performance in the future (Mortimer & Wertsch, 2003; Wertsch & Kazak, 2005; Wood et al., 1976). In short, scaffolded performance leads to skill gain that can only lead to independent performance when a student also exhibits interdependence.

Before proceeding further, it is important to acknowledge the lack of precision that has emerged in the term *scaffolding* as researchers used the term to describe a wide swath of instructional methods. This has been an often-lamented phenomenon (Pea, 2004; Puntambekar & Hübscher, 2005; Stone, 1998). I did not set out to resolve this debate, as that is beyond the scope of this book. Still, it is important to outline what the term *scaffolding* means for the purposes of this book. The first key feature that distinguishes scaffolding from other forms of instructional support is that it is temporary support that is provided as students are engaging with problems (Belland, 2014; Collins et al., 1989; Wood et al., 1976). As a corollary, support that is not provided as students engage with problems (e.g., it is provided before students engage with problems or it is provided as students listen to a lecture) is not scaffolding. According to this definition, one cannot give instruction to students, then have them engage in practice problems, and call the instructional intervention scaffolding. Support that continues indefinitely does not meet the scaffolding definition either, as this would not require that students gain skill so as to be able to perform the target task independently in the future (Collins et al., 1989; Wood et al., 1976).

Next, scaffolding needs to lead to skill gain such that students can function independently in the future (Belland, 2014; Pea, 2004; Wood et al., 1976). Hence, tools such as a calculator cannot be considered scaffolds because they are not meant to lead to learning. Rather, such tools are meant to continue to be used whenever users encounter a situation in which the tools are of use (e.g., finding square roots, dividing large numbers). To the contrary, scaffolding needs to simultaneously help students enhance skills and participate meaningfully in the performance of the target skill (Belland, 2014; Wood et al., 1976).

Third, scaffolding not only simplifies tasks, but also highlights complexity therein (Reiser, 2004; Wood et al., 1976). This is because struggling while attending to certain complexities inherent in a particular task can lead to robust learning (Reiser, 2004; Simons & Ertmer, 2006). A job aid does not meet the definition of scaffolding already because it is not meant to lead to learning, but it also is disqualified because it only simplifies tasks and does not highlight complexity therein (Belland, 2014).

Fourth, to qualify as scaffolding, students need to meaningfully participate in the target task and have an understanding of what success at the task means (Mahardale & Lee, 2013; Wood et al., 1976). If the tool does all or most of the work or if students do not know how to recognize successful performance of the target skill, then the possibility of skill gain is compromised (Chi, 1996; Pea, 2004).

2.2 Scaffolding Elements

Next, it is important to describe in detail the elements that contingency of scaffolding encompasses—dynamic assessment, providing just the right amount of support, and intersubjectivity.

2.2.1 Dynamic Assessment

Dynamic assessment and scaffolding customization were inextricably tied (See Fig. 2.1) in the original scaffolding definition (Wood et al., 1976). Dynamic assessment differs in goals and methods from traditional assessment in that it (a) aims at not only ascertaining the current level of performance, but also improving it, (b) aims at informing appropriate instructional practices, rather than simply classification, and (c) focuses on students' current and potential levels of performance

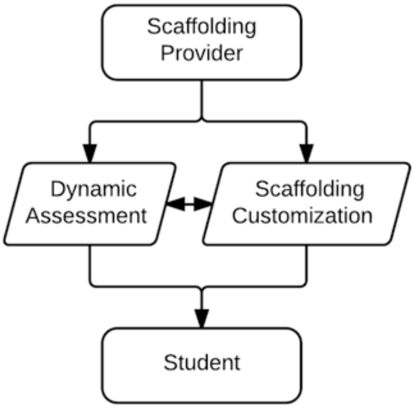

Fig. 2.1 The role of dynamic assessment in the customization of scaffolding

(Lidz, 1995; Seethaler, Fuchs, Fuchs, & Compton, 2012; Tzuriel, 2000). For example, dynamic assessment can involve providing a series of prompts that each provide differing levels of support; the teacher can then determine the student's current ability level based on what level of support was needed to enable adequate performance (Lidz, 1995; Seethaler et al., 2012). Dynamic assessment can also involve having students perform a task in the genre of the target task, noting their difficulties, designing tailored assistance, providing that, and assessing the student's ability (Tzuriel, 2000). Dynamic assessment can also focus on eliciting the metacognitive processes in which students engage and comparing those to the type of metacognition that is desired (Lidz, 1995). Within dynamic assessment, there is often also a focus on seeing what students can do in collaboration with others, which harkens back to the original definition of the zone of proximal development (Kozulin & Garb, 2002; Vygotsky, 1978). For example, teachers may draw student attention to particular concepts in questions or instructions in tests, thereby assessing students' abilities to conduct the tasks embedded in the test, rather than their ability to interpret instructions (Kozulin & Garb, 2002).

Dynamic assessment can be both a stand-alone intervention—and a highly effective one at that (Seethaler et al., 2012; Swanson & Lussier, 2001; Tzuriel, 2000); for more information, see Swanson and Lussier (2001)—and the basis for adjustment of scaffolding (Poehner & Lantolf, 2005; van de Pol, Volman, & Beishuizen, 2010; Wood et al., 1976). When used as the basis for the provision of teacher scaffolding, teachers ask questions and observe student performance to determine the level of support that is needed and then provide support accordingly (van de Pol et al., 2010).

Dynamic assessment can also be used for adjustment of scaffolding that is already being provided. In this case, teachers can determine the extent to which student skill is improving so as to lead to success without scaffolding, or with less scaffolding, and such adjustments can be made in real time. When used as the basis for the introduction, removal, or adjustment of computer-based scaffolding, students often need to respond to multiple choice questions (Koedinger & Aleven, 2007; VanLehn, 2011). The veracity of the responses or lack thereof is then fed into model tracing in the intelligent tutoring system, and the level of support is thereby increased or reduced (Baker, Corbett, & Koedinger, 2007; Koedinger & Corbett, 2006; Murray, 1999). However, adjustment of computer-based scaffolding is often not performed on the basis of dynamic assessment, but rather on the basis of self-selection or a fixed schedule, especially in the case of scaffolding to support ill-structured problem-solving (Belland, 2011; McNeill, Lizotte, Krajcik, & Marx, 2006; Metcalf, 1999). This results from difficulties in programming computer tools to dynamically assess how well students are performing in ill-structured problem-solving, when there are countless paths that can be taken that are equally correct. Self-selected or fixed customization may not fit the original definition of scaffolding customization (Belland, 2011; Wood et al., 1976).

2.2.2 Providing Just the Right Amount of Support

First, providing just the right support refers to providing scaffolding support according to what dynamic assessment indicated was required (Wood et al., 1976). This can be either providing customized support generated in real time, as in one-to-one scaffolding (Jadallah et al., 2010; van de Pol, Volman, & Beishuizen, 2012), or providing just the right combination of preformed scaffolding elements, as can occur with computer-based scaffolding (Koedinger & Corbett, 2006).

Next, providing just the right amount of support depends upon adjustment in one or more of the following ways—adjustment to (a) the support strategies being used, (b) the subskill on which to focus next, and (c) the timing by which support is offered (Wood, 2003). One form of such adjustment—removing support—was later termed "fading" by Collins et al. (1989). In fading, the scaffolding provider removes or lessens the intensity of scaffolding based on dynamic assessment that indicates improved performance and the potential to perform well independently. Fading is designed to gradually transfer the responsibility for the performance of the target skill from the scaffold provider to the scaffold receiver (Collins et al., 1989; van de Pol et al., 2010). For example, fading may first lead to a shift to scaffolding strategies that are less supportive or directive and eventually to an absence of all scaffolding strategies altogether. As another example, the initial scaffolding strategy may help students overcome three major challenges in the target task, but after fading, the scaffolding strategy may only support learners in overcoming one or two of the challenges. Fading can also refer to a decrease in the frequency of scaffolding messages. It has been proposed that fading may not be a necessary prerequisite of transfer of responsibility in all cases; rather, ensuring that students maintain executive control of the underlying activity can lead to the transfer of responsibility from the scaffold to students (Belland, 2011).

Scaffolding adjustment can also take the form of adding different types of support or enhancing the support that was already present, this based on dynamic assessment that indicates that students are not making the necessary progress quickly enough to lead to independent problem-solving, or self-selection (Koedinger & Aleven, 2007; Koedinger & Corbett, 2006). As with fading, the exact nature of adding support can vary. It can manifest itself in (a) providing more scaffolding strategies, or more supportive ones, (b) scaffolding targeting more challenges, and/or (c) exposing students to scaffolding messages more frequently (Baker et al., 2007; Koedinger & Aleven, 2007; Murray, 1999). Adding scaffolding often happens when students click a button indicating that they want more help (hints), as is the case with intelligent tutoring systems (Koedinger & Aleven, 2007; Koedinger & Corbett, 2006). In this case, the first time the hint button is pressed, a minimally supportive hint is given. The next times, successively more supportive hints are given each time, until a bottom-out hint is given that contains the solution (Koedinger & Aleven, 2007). Such self-selection of hints can be tied to the position of the theoretical basis of intelligent tutoring systems—Adaptive Character of Thought (ACT-R)—that struggle is unproductive in learning (Anderson, 1983). In intelligent tutoring systems, hints can also be provided based on performance, but this is less common (Koedinger & Aleven, 2007).

Scaffolding interventions can also employ both strategies—adding and fading—depending on what the performance characteristics of the learner justifies (Koedinger & Corbett, 2006). That is, if performance characteristics indicate that the student is not making sufficient progress, scaffolding can be added. If performance indicators indicate that the student is on the path to being able to perform the target skill independently, then scaffolding can be faded. This is employed by providers of one-to-one scaffolding (Chi, 1996; van de Pol et al., 2010), but also often by intelligent tutoring systems (Koedinger & Corbett, 2006). In the latter case, this often involves feedback that varies depending on the quality of students' performance (adding/fading) as well as hints that are available on demand (adding; Koedinger & Corbett, 2006).

Ultimately, the goal of scaffolding is that the learner not only gains the skills required to perform the target task independently, but also assumes responsibility for the task (Belland, 2014; Wood et al., 1976). In other words, scaffolding aims at promoting not only the capacity but also the willingness to perform complex tasks independently (Belland, Kim, et al., 2013). Lying beneath the surface of this aim are cognitive and motivational aims, neither of which, if satisfied, would be enough by itself to ensure success (Belland, Kim, et al., 2013; Wood et al., 1976). Perhaps accordingly, in its initial conceptualization, scaffolding included equal parts support for motivation (recruitment, frustration control, and direction maintenance), and cognition (marking critical features, demonstration, and reduction in degrees of freedom; Belland, Kim, et al., 2013; Wood et al., 1976). Such support built off of toddlers' existing skills and knowledge and was delivered as the toddler engaged with the problem. Within the example from Wood et al. (1976) in which adults helped infants learn to build pyramids, recruitment built off of the interest toddlers developed during free play with the wooden blocks prior to the application of the scaffolding approach. Central to the development of interest is establishing the importance of the learning activity to learning to perform the target skill (Gu, Belland, Weiss, Kim, & Piland, 2015). Frustration control helped keep learners invested in the task at hand even when they ran into the inevitable struggles that characterize authentic problem-solving. Direction maintenance aimed at keeping students on the path that would lead to solving the problem. Within marking critical features, tutors could point out the most critical factors to which students should attend. Demonstration relied on students' existing knowledge of how to put blocks together, extending such knowledge by showing students how to combine moves that they had already performed in new ways. When reducing the degrees of freedom, tutors would simplify the process such that students only need pay attention to the segment of the task that will lead to learning gains. Notably, all such scaffolding strategies built off of what students could already do, and extended such capabilities so as to enable more complex activity (Wood et al., 1976; Wood & Wood, 1996).

2.2.3 Intersubjectivity

Also crucial to the definition of scaffolding and to the idea of transfer of responsibility was intersubjectivity, according to which students needed to recognize an appropriate solution to problems similar to the one being addressed before they would be able to perform the supported task independently (Mahardale & Lee, 2013; Mortimer & Wertsch, 2003; Wood et al., 1976). Without intersubjectivity, students are said to be unable to engage in independent performance of the target skill (See Fig. 2.2).

Intersubjectivity can be achieved without knowledge of how to perform the skill that scaffolding is intended to develop (Wertsch & Kazak, 2005). It is important to note that it is not required that the understanding be exactly the same, as partners in an activity likely hold differing perspectives, which can shape an understanding of a task (Rogoff & Toma, 1997). Furthermore, if the child and adult had an entirely identical understanding of what an appropriate solution would be to a problem similar to that being addressed, then the child may not need scaffolding (Wertsch, 1984). Rather, the understanding of the task should be substantially similar between the scaffolding provider and the student. This was said to be crucial because students needed to be able to recognize when what they were doing was successful when they attempted the target tasks independently in the future (Mortimer & Wertsch, 2003; Wood et al., 1976). In short, scaffolding could help students with how to ac-

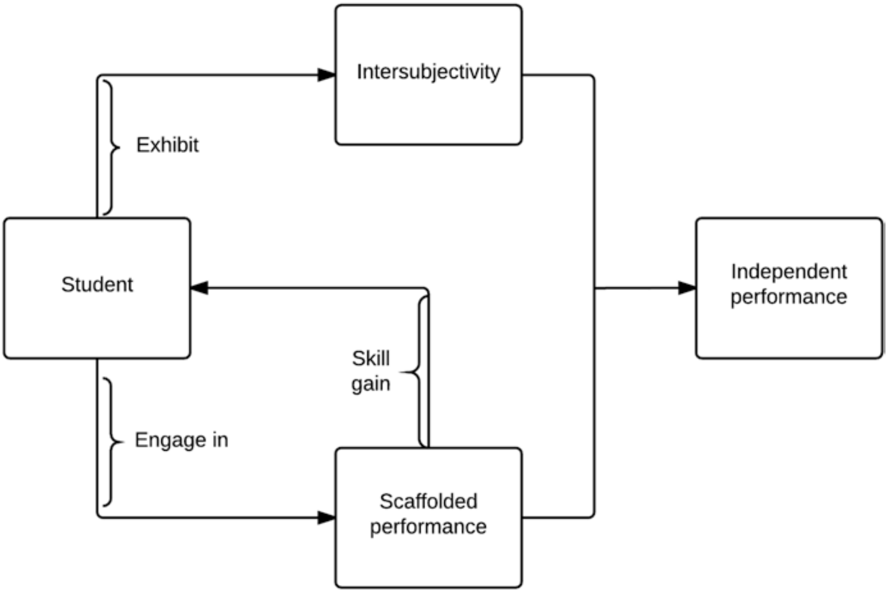

Fig. 2.2 Exhibiting intersubjectivity and engaging in scaffolded performance as predictors of the ability to engage in independent performance

complish a given task, but was not suited to also establish the evidence that would indicate that an appropriate solution had been found to problems of similar types.

Scaffolding can be provided by teachers (one-to-one scaffolding), peers (peer scaffolding), and computers (computer-based scaffolding) (Belland, 2014). In the next section, the scaffolding forms are defined and changes in the scaffolding definition to encompass computer-based scaffolding are discussed.

2.3 Scaffolding Forms

Scaffolding forms include one-to-one, peer, and computer-based scaffolding (See Table 2.1). These are explained in depth in the subsections that follow.

2.3.1 One-to-One Scaffolding

One-to-one scaffolding is defined as one teacher working one-on-one with one student to dynamically assess the student's current level, provide just the right amount of support for the student to perform and gain skill at the target task, and customize the support as needed until the scaffolding can be entirely removed and the student can take ownership (Belland, 2014; Chi, 1996; Graesser, Bowers, Hacker, & Person, 1997; Lepper, Drake, & O'Donnell-Johnson, 1997; van de Pol et al., 2010). Within one-to-one scaffolding, it is helpful to think of scaffolding intentions—what the teacher seeks to accomplish by scaffolding—and scaffolding means—the specific

Table 2.1 Overview of one-to-one, computer-based, and peer scaffolding

	One-to-one scaffolding	Computer-based scaffolding	Peer scaffolding
What is it?	One teacher working one-to-one with one student	Scaffolding function fulfilled by a computer tool that can be embedded into a curriculum or a tool that students use when engaging with a problem outside of the system	Scaffolding support provided by peers of similar or greater ability
Among scaffolding forms, what are its relative advantages?	Leads to the strongest influence on learning outcomes Is the best at dynamic customization	Is the most scalable Has infinite patience	Is the most scalable scaffolding form that still involves one-to-one interaction
Among scaffolding forms, what are its relative disadvantages?	Least scalable	Least dynamic	Scaffolding provider is not necessarily more able

strategies used (Belland, 2012; van de Pol et al., 2010). One-to-one scaffolding intentions include recruiting, structuring tasks, direction maintenance, reducing the degrees of freedom, and frustration control (van de Pol et al., 2010). One-to-one scaffolding means include modeling, questioning, explaining, giving hints, and providing feedback (van de Pol et al., 2010). Some of these same techniques are used in the context of other instructional approaches, so it is important to consider both intentions and means when considering one-to-one scaffolding (Belland, 2012). For example, to promote increased use of evidence in arguments, fourth grade teachers used such scaffolding means as praise and prompting for evidence, which led to enhanced use of evidence by the students (Jadallah et al., 2010). To promote the consideration of the relations between different entities involved in a problem, teachers can prompt students to consider such relations and illustrate how to do so; this led elementary students to successfully consider such relations (Lin et al., 2014). In another example, teachers can use questioning and other strategies to help struggling first grade students learn to read; this helped such students rapidly reach grade-level reading proficiency (Rodgers, 2004). Praise and prompting for evidence can very well be used as part of another instructional approach. What makes the strategies examples of scaffolding has to do with the intended function of the strategy and the context in which it was used (e.g., to help students engaged in authentic problem-solving (Belland, 2012)).

Due to its highly contingent nature, one-to-one scaffolding is generally considered to be the ideal form of scaffolding (Belland, Burdo, & Gu, 2015; Chi, 1996; Graesser et al., 1997). Among scaffolding forms, it tends to lead to the highest effect sizes as indicated by a recent meta-analysis, which found that one-to-one scaffolding leads to an average effect size of 0.79, while step-based intelligent tutoring systems led to an average effect size of 0.76 (VanLehn, 2011). Still, in most educational environments, one cannot expect all needed support to come from one-to-one scaffolding (Belland, Gu, Armbrust, & Cook, 2013; Muukkonen, Lakkala, & Hakkarainen, 2005; Puntambekar & Kolodner, 2005). Thus, it is important to focus one-to-one scaffolding to those areas where it is most effective and allow computer-based scaffolding to shoulder the lion's share of responsibility for supporting students in the remainder of the areas in which students need support (Belland, Gu, et al., 2013; Muukkonen et al., 2005; Saye & Brush, 2002).

2.3.2 Peer Scaffolding

Peer scaffolding refers to the provision of scaffolding support by peers, and it leverages the strength in numbers of peers in classrooms (Davin & Donato, 2013; Pata, Lehtinen, & Sarapuu, 2006; Sabet, Tahriri, & Pasand, 2013). But it can also involve older children providing scaffolding support to younger students. For example, students with strong English-speaking abilities can use questioning and prompting to help English as a New Language students improve their English-speaking abilities (Angelova, Gunawardena, & Volk, 2006). In another example, third grade students provided scaffolding support to help preschool students create crafts projects (Fair, Vandermaas-Peeler, Beaudry, & Dew, 2005).

Peer scaffolding requires that a framework be provided that guides scaffolding (Belland, 2014). Such a framework can guide scaffolding providers with strategies to use and when to use them (Belland, 2014). The framework can be embedded in computer-based scaffolds. For example, students can be encouraged to provide feedback through the embedding of a peer feedback mechanism in computer-based scaffolds, as well as guidance on how to provide peer scaffolding in this way (Pifarre & Cobos, 2010). Doing so can help college students regulate each other's learning behavior (Pifarre & Cobos, 2010).

Individual empirical studies indicate that peer scaffolding positively influences cognitive outcomes (Fair et al., 2005; Hakkarainen, 2004; Oh & Jonassen, 2007; Palincsar & Brown, 1984; Pifarre & Cobos, 2010) and helps students who are low in self-regulation successfully address the central problem (Helle, Tynjälä, Olkinuora, & Lonka, 2007), but to my knowledge no comprehensive meta-analysis addresses this form of scaffolding. One meta-analysis covers the influence of peer tutoring, finding that it leads to an average effect size of 0.4 (P. A. Cohen, Kulik, & Kulik, 1982).

It is unlikely that peer scaffolding would be sufficient as a sole source of scaffolding support, as similarly abled peers do not have the content or pedagogical expertise to be able to engage in the dynamic assessment and customization that is characteristic of one-to-one scaffolding (Belland, 2014). Peers also often do not have the patience and persistence of a computer program. Furthermore, when peer scaffolding providers are at the same grade and ability level as the peer scaffolding receivers, one may question the capacity for strong scaffolding interactions. However, research on the influence of content expertise of tutors on learning outcomes in problem-based learning is often contradictory (Albanese, 2004; Dolmans et al., 2002). A recent meta-analysis indicated that student learning decreases as tutor expertise increases (Leary, Walker, Shelton, & Fitt, 2013).

2.3.3 Computer-Based Scaffolding

One-to-one scaffolding is a very effective method. A recent meta-analysis found that it leads to an average effect size of 0.79 on cognitive learning outcomes (VanLehn, 2011), which is classified as a large effect size according to J. Cohen's (1969) guidelines. But it was clear that one teacher in a classroom of 30 students would not likely be able to provide all of the scaffolding support that her students would need (Saye & Brush, 2002; Tabak, 2004). Thus, computer-based scaffolding emerged as a tool to help share in the burden of scaffolding (Hawkins & Pea, 1987).

Computer-based scaffolding can be defined as computer-based support that helps students engage in and gain skill at tasks that are beyond their unassisted abilities (Belland, 2014; Hannafin, Land, & Oliver, 1999; Quintana et al., 2004). Specifically, it assists students as they generate solutions to complex, ill-structured problems and is provided entirely by a computer-based tool. This means that the tool helps extend student capabilities such that they are able to perform at a higher level than they would have otherwise. For example, *Belvedere* invites students to articulate important concepts that interrelate in the problem and diagram and characterize links among these concepts through concept mapping (Cavalli-Sforza, Weiner, & Lesgold, 1994; Cho & Jonassen, 2002).

The exact nature of support in computer-based scaffolding varies according to the theoretical framework—e.g., cultural historical activity theory, ACT-R, or knowledge integration—on which the scaffolding is based. Support created according to the activity theory framework is designed to stretch student abilities and foster the kind of struggle that the framework holds leads to learning (Akhras & Self, 2002; Belland & Drake, 2013; Jonassen & Rohrer-Murphy, 1999; Reiser, 2004). Computer-based scaffolding created according to the ACT-R framework is designed to help students apply declarative knowledge in the context of problems such that they can develop production rules with which to use the target knowledge in the context of solving new problems (Koedinger & Corbett, 2006; VanLehn, 2011). Such scaffolding is designed so as to help students avoid struggle, which ACT-R posits as inconducive to learning (Anderson, 1996). Computer-based scaffolding designed according to the knowledge integration framework aims to help students build integrated mental models while they engage with problems (Clark & Linn, 2013; Linn, Clark, & Slotta, 2003). Computer-based scaffolding is largely less contingent than one-to-one scaffolding, although, in general, scaffolding embedded in intelligent tutoring systems is more contingent than other computer-based scaffolding.

Recent smaller-scale meta-analyses showed that computer-based scaffolding led to average effect sizes of 0.53 (Belland, Walker, Olsen, & Leary, 2015) and 0.44 (Belland, Walker, Kim, & Lefler, 2014). In the meta-analysis from which this book grew, the average effect size of computer-based scaffolding was 0.46 (Belland, Walker, Kim, & Lefler, In Press). This is higher than the median effect size among meta-analyses of interventions in psychological research ($g=0.324$) (Cafri, Kromrey, & Brannick, 2010). It is also higher than the average effect size of educational technology applications designed for mathematics education ($ES=0.13$) found in a recent review (Cheung & Slavin, 2013) and that of educational technology applications designed for reading instruction ($ES=0.16$) (Cheung & Slavin, 2012). Computer-based scaffolding has been seen to have a very substantial effect size in prior research, as compared to that of similar interventions, and this warrants further research.

2.4 Considerations as the Instructional Scaffolding Metaphor was Applied to Computer Tools

The application of the instructional scaffolding metaphor to computer-based tools entails several new considerations, including the theoretical bases of computer-based scaffolding, how computer-based scaffolding should be designed, and the interplay between computer-based and one-to-one scaffolding (Belland & Drake, 2013; Belland, Gu, et al., 2013; Puntambekar & Hübscher, 2005). As noted earlier, there are several traditions of computer-based scaffolding, each of which are based in different learning theory bases, including activity theory, ACT-R, and knowledge integration. This diversity of learning theory bases of scaffolding is not entirely unexpected, as Wood et al. (1976) never explicitly referenced learning theory in their seminal paper. The different theoretical bases inform how computer-based scaffolding is designed, what strategies it incorporates, and the role of the teacher in the support of student learning.

2.4.1 Theoretical Bases of Computer-Based Scaffolding

Instructional scaffolding was originally proposed to describe how teachers supported children as they learned to build with wooden blocks (Wood et al., 1976). What is often forgotten is that Wood et al. (1976) did not link scaffolding to a particular theoretical foundation. Rather, their paper was an attempt to describe how a tutor helped children put together wooden blocks to create shapes. Thus, while some theory figures into the paper, the authors did not describe the use of theory to design the scaffolding process. To the contrary, the description of the scaffolding process was grounded in observations of what actions the tutor took that led to student success. So in this way, the development of the scaffolding metaphor roughly followed the grounded theory approach (Glaser & Strauss, 1967). But, to help inform the design of scaffolding, later researchers attempted to link the construct to multiple theoretical bases. This plurality of underlying theoretical bases corresponds with different scaffolding approaches and different contexts in which scaffolding is used (Wood & Wood, 1996).

Three primary theoretical bases of instructional scaffolding are activity theory, ACT-R, and knowledge integration. In this chapter, I describe these theoretical bases such that different approaches to scaffolding can be more easily understood.

2.4.1.1 Activity Theory

First, much scaffolding is linked to the social constructivism seen most prominently in the work of Vygotsky (1978), Leont'ev (1974), and Luria (1976). Commonly called activity theory, it likely made sense in the context of scaffolding in that Vygotsky famously based much of his work on the idea of a zone of proximal development—the set of tasks in which students could meaningfully participate with assistance (Smagorinsky, 1995; Vygotsky, 1978). Though it does not encompass all of Vygotsky's work, and there are certainly many other important contributors to activity theory, the critical underlying learning theory for scaffolding from this perspective is cultural-historical activity theory (Belland & Drake, 2013; Pea, 2004)—a theory that was largely developed in the Soviet Union, in part due to an exhortation to apply the tenets of dialectical materialism to learning (Luria, 1979).

2.4.1.1.1 Theoretical Background

A central premise of cultural-historical activity theory is that the genesis of the development of new skills is in the external processes in which people engage (Kozulin, 1986; Leont'ev, 1974; Luria, 1976). This forms a sharp contrast with the assumptions of behaviorist theories of a stimulus-response origin of learning (Skinner, 1984), and that of information processing theories that learning occurs from the reception of new content and the subsequent use of encoding strategies such as mnemonics and rehearsal (Ausubel, 1980; Miller, 1956). According to an activity theory perspective, learning is not one's reaction to the introduction of stimuli and associated reinforcement and reinforcement removal or the use of rehearsal, mnemonics, and other cognitive strategies, but rather is the internalization of cultural and other knowledge inherent in external activity (D'Andrade, 1981; Leont'ev, 2009; Luria, 1976). The cultural knowledge can be embedded in such instructional support as computer-based scaffolding (Belland & Drake, 2013; Jonassen & Rohrer-Murphy, 1999), or embedded in the support provided by and interactions with other individuals (Engeström, 2009; Roth & Lee, 2007).

According to activity theory, the external processes in which humans engage are shaped by a complex interaction between three entities—the individual, his/her motives (goals), and signs (Leont'ev, 1974; Luria, 1979). From the perspective of an individual, a sign is the concept (signified concept) that another individual or object (signifier) represents (Barthes, 1994; Wertsch & Kazak, 2005). This representation can include what the individual thinks can be accomplished with the other individuals or objects, or what the object invites the individual to do. This perspective is informed by semiotics, which highlights the importance of individual perceptions when interacting with other individual and tools (Barthes, 1994). These individual perceptions can influence how individuals interact with other individuals and tools. From a semiotic perspective, each object has a signifier (form) and a signified concept (what the object represents). For example, in the USA, the signifier of a stop sign is usually octagonal, red, and includes the writing "Stop." However, the signified concept can vary among citizens. For some, it represents a suggestion to slow down. For others, it represents an order to stop and look both ways before proceeding through the intersection. Signs are arbitrary and are attached to entities by groups or individuals on the basis of culture and history (Saffi, 2005). For example, there is nothing inherently sinister about clowns. Yet among many groups in Western cultures, clowns evoke a feeling of evil. This is due to the signification generated by the history (e.g., the serial killer John Wayne Gacy) and culture of the group. Society imposes or suggests classifications of objects (Barthes, 1994). However, society does not impose the same classification to everyone because not all people experience the same society (Barthes, 1994). Classification of objects helps determine the meaning that signs will hold to individuals or groups. Individuals then interact with signs based on the signs' meaning.

Goals underlie all activity, and can be influenced by cultural and historical factors (Leont'ev, 2009). In this way, one would expect to see differences in approaches to actions between different cultures; indeed, such was found in the research of Luria

(1976) and Vygotsky (1978). Goals are crucial to the building of signs (Belland & Drake, 2013). It is important to recognize that goals are not always consciously identified and pursued (Locke & Latham, 2006). Nonetheless, such goals still form an important influence on the building of signs and, in turn, action (Saffi, 2005).

As an example of how individuals' cultures can shape their perception of a tool, consider language. Language can be a tool of symbolic violence, and the way in which it does or does not have the potential to be used in that way depends on one's culture and, specifically, subculture (Bourdieu, 1982). One's perception and use of language can then influence thought patterns.

Thus, different individuals can build signs about tools and individuals in different ways. This means then that they would perceive the tools and individuals as being useful to help accomplish different tasks.

2.4.1.1.2 How New Skills Are Generated According to Activity Theory

The use of tools and strategies can help learners gain cultural knowledge, as these reflect the core assumptions and ways of knowing of the target culture. Cultural knowledge can include constraints and guidance on how to categorize and count certain things (D'Andrade, 1981; Kozulin, 1986; Luria, 1976), symbol systems that frame how one views phenomena (Bourdieu, 1982; D'Andrade, 1981), and approaches to certain tasks (D'Andrade, 1981; Luria, 1976). In this way, cultural patterns of interaction and ways of knowing are core to learning.

From an activity theory perspective, the goal of instruction is to provide the tools and frameworks by which students can engage in the types of external actions that will allow them to internalize and integrate the desired content (Belland & Drake, 2013; Jonassen & Rohrer-Murphy, 1999). Such tools and frameworks may embed representations of the cultural knowledge that one wishes to instill in students. By interacting with such tools and frameworks, individuals may have the opportunity to construct the target cultural knowledge. But this does not happen instantaneously; rather, it may be necessary to engage with several problems supported by the tools and frameworks to succeed in constructing the target cultural knowledge. It is also clear from activity theory that simply providing a set of tools and frameworks is not sufficient because individuals may interact with and use such differently based on their different experiences of culture and history (Belland & Drake, 2013; Leont'ev, 2009; Luria, 1976).

2.4.1.1.3 How Activity Theory Informs Instruction

According to activity theory, productive interaction with tools and other individuals in the process of solving authentic problems leads to learning (Leont'ev, 1974; Luria, 1976). It follows that instructional approaches aligned with activity theory stress the importance of collaboration and solving authentic problems (Jonassen & Rohrer-Murphy, 1999; Roth & Lee, 2007). Tools play a central role in instruction informed by activity theory, but there is a recognition that the function of the tools provided to learners can vary, even when the physical form of the tools stays the same (Belland, 2010; Belland & Drake, 2013; Belland, Gu, Armbrust, & Cook, 2015).

An instructional approach grounded in activity theory takes a decidedly postmodern approach, in that it allows for multiple approaches and recognizes the importance of individual perspectives and those of members of the culture in which the student is operating (Friesen, 2012; Hlynka, 2012; Solomon, 2000). Furthermore, such an approach would welcome the type of critique and dialogue that one would expect to see in a scientific laboratory or conference/publishing venue. Thus, such approaches would likely involve addressing a central, ill-structured problem (Jonassen, 2011; Jonassen & Rohrer-Murphy, 1999). Furthermore, students would be provided considerable latitude to address the problem in the manner that best suited them.

2.4.1.1.4 How Activity Theory Informs Scaffolding

Activity theory can describe the social mediation process of scaffolding (Engeström, 2009; Jonassen & Rohrer-Murphy, 1999; Roth, 2012). Goals can influence how learners interpret and use scaffolds (Belland & Drake, 2013; Belland, Glazewski, & Richardson, 2011). Specifically, when learners view scaffolds, they do not all see the same thing; rather, they build a sign based on goals and cultural and historical factors (Belland & Drake, 2013; Leont'ev, 1974; Wertsch, 1991). A sign refers to the learners' internal representation of what the tool is, what it should be used for, and what can be accomplished with it (Belland & Drake, 2013; Wertsch, 1991). Learners build signs on the basis of culture and history—one's individual history with similar tools and the situations in which they are used (Belland & Drake, 2013). Furthermore, due to the influence of culture and history on their definition, signs are not the same for all individuals, since by definition each individual will experience different cultural influences and histories (Barthes, 1994; Saffi, 2005). When students interact with the scaffold, they interact with the sign (i.e., signified concept) rather than with a static, unchanging tool (Belland & Drake, 2013). This means that different learners can see and use scaffolds in different ways (Belland, 2010; Belland & Drake, 2013; Belland et al., 2011). Thus, when designing scaffolding, it is important to think about the processes and situations in which the scaffolding will be used (Akhras & Self, 2002; Belland & Drake, 2013).

Activity theory explains that tools such as scaffolding do not merely transmit human action from one forum to another, as an ax transmits the force produced by swinging one's arms to the surface area of the blade. Rather, as a psychological tool, scaffolding transforms and extends human action first in external action, and then that same transformed external action can be internalized (Belland & Drake, 2013; Kozulin, 1986). In this way, the cultural knowledge inherent in the scaffold can be internalized in the learner. Cultural knowledge can be defined as knowledge, tendencies, and skills that are shared by a group of people (Hogan & Maglienti, 2001;

Leont'ev, 1974; Luria, 1976). Cultures in this case refer not only to national cultures like German or Indonesian, but can include members of an occupation (e.g., civil engineers, bankers) or of a particular interest group (e.g., bird watchers, coin collectors). For example, the cultural knowledge of civil engineers may include methods to elicit and prioritize client needs when discussing a project. The cultural knowledge of bird watchers may include strategies to quickly distinguish between the calls of different species of birds. Cultural knowledge is often implicit, in that members are not always consciously aware of it. To succeed at thinking or acting like a member of a particular culture, it is important to take into account cultural knowledge and incorporate such into support (e.g., scaffolding).

In short, scaffolding informed by cultural-historical activity theory seeks to help learners use cultural tools as they engage in higher-order tasks, and assimilate such into their own practice (Belland & Drake, 2013; Jonassen & Rohrer-Murphy, 1999). This in turn helps students develop higher-order psychological processes (Vygotsky, 1962). Thus, from an activity theory perspective, when designing scaffolding, it is important to think broadly about the dispositions and modes of thinking that one wishes to develop in students, rather than about discrete skills students need to develop (Akhras & Self, 2002; Belland & Drake, 2013). This may be accomplished through the use of ethnographies of the professions of interest. This can allow designers to find out the key dispositions and thinking strategies employed by members of the profession and then think about how such can be applied in problems that are accessible to the student population.

2.4.1.2 ACT-R

Much research views scaffolding as a vehicle to promote student learning of higher-order skills through the creation and optimization of production rules and learning of declarative knowledge (VanLehn, 2011). Such production rules can then be used in sequence to produce the target higher-order skill. This view of scaffolding draws on the Adaptive Character of Thought-Rational (ACT-R) learning theory (Anderson, 1996).

2.4.1.2.1 Theoretical Background

In cognitive science, there has long been a push to develop a unitary theory of cognition (Laird, 2008; Newell, 1973). According to this idea, rather than develop many specialized theories and conduct various investigations about different cognitive phenomena, cognitive scientists and psychologists should strive to develop and test a theory by which all human cognition can be explained. If true, such a theory would show that all human cognition is the product of the application of differing combinations of the same subskills (Anderson, 1983, 1990). According to a unitary theory of cognition, there is nothing special about any cognition—that any thought, be it a breakthrough or simply a determination of what to eat for lunch, is an assemblage of various components of the same set of declarative knowledge and production rules (Anderson, 1983; Laird, 2008). Within this context, John Anderson and colleagues developed a series of learning theories—the ACT series of theories of cognition—and attempted to posit these as unitary theories of cognition (Anderson, 1983, 1990). Anderson and colleagues have worked on the development and testing of intelligent tutoring systems in part to test and refine the tenets of ACT theories of cognition (Anderson et al., 1997; Koedinger & Corbett, 2006).

ACT-R is a recent version of the ACT series of theories of cognition. Lying behind ACT-R is a theory of rational action, of which a critical assumption is that people will always consciously choose to act in the manner that they perceive best serves their own interests (Anderson, 1990). This draws on research related to the theory of reasoned action, according to which, in the aggregate, people act in accordance with salient personal beliefs (Ajzen, 1991). This does not imply a conscious decision to act in accordance with the salient belief before each action (Ajzen, 1991; Anderson, 1990). For example, personal beliefs about the efficacy of a particular strategy can predict one's attitudes about the strategy and, in turn, propensity to use such strategy in a salient situation (Ajzen, 1991).

In the context of ACT-R, it is important to note that rational action implies that there are goals inherent in cognitive systems (Anderson, 1990). Such goals are specified in the way that a problem is framed (Anderson, 1990). Once such goals are identified, individuals determine the most appropriate production rules and declarative knowledge to deploy to achieve the goals (Anderson, 1990). Such decisions are informed with reference to utility values that were generated in the creation of the production rule and thus associated with the latter. When individuals are confronted with a new problem, they search through the available production rules, and pick the one that has the highest utility value for the situation (Anderson et al., 2004).

According to ACT-R, a cognitive theory needs only concern itself with three levels of analysis: the biological level, the algorithmic level, and the rational level (Anderson, 1990). The biological level is what resides in the head. One cannot model it exactly, but one can approximate it through the use of an implementation model. The algorithmic level is the set of procedures and strategies by which information can be encoded, retrieved, and deployed in problem-solving (Anderson, 1987, 1990). The rational level concerns the constraints to which cognition needs to adhere to be rational, defined as working towards the agent's goals (Anderson, 1990).

2.4.1.2.2 How New Skills Are Generated According to ACT-R

Using ACT-R, complex skills can be broken down into knowledge chunks and production rules, which dictate how to apply the knowledge to solve problems (Anderson, 1996). Knowledge chunks all encode two or more elements, and how they relate (Anderson, 1983). Chunks never exceed seven elements, as informed by the cognitive information processing theory finding that one can at most manipulate 6–8 pieces of information in short-term memory at a time (Miller, 1956). For example, chunks can include (relation: love, agent: baby, object: pacifier), (relation: hate, agent: baby, object: dirty diaper), and (relation: hate, agent: baby, object: hunger). According to ACT-R, one cannot directly teach production rules. Rather, one needs to teach the knowledge associated with the production rule in declarative form and invite the learner to practice applying the knowledge in the context of problems. In other words, all knowledge begins in declarative form, and can become procedural when students have applied it enough to authentic problems (Anderson, 1983; Anderson et al., 2004). When students first learn knowledge chunks and attempt to apply such, they do so using general procedures (Anderson, 1983). This process requires the students' active interpretation. For example, new parents might apply the knowledge chunks (relation: love, agent: baby, object: pacifier), (relation: hate, agent: baby, object: dirty diaper), and (relation: hate, agent: baby, object: hunger) in succession when their baby cries. Desperate to console the baby, they attempt to interpret what the baby wants by applying the chunks using the general framework that when someone is unhappy, it is important to figure out the root of the unhappiness and that one can do so through the process of elimination. As they apply the new knowledge enough using general procedures, they begin to develop production rules—strategies that they can employ without the use of active interpretation. In other words, the student knows that in X situation, one can apply knowledge chunk Y using strategy Z, and can apply strategy Z in X situation without actively interpreting the situation (Anderson, 1983). People are not always consciously aware of production rules, but not being consciously aware of production rules does not prevent their application (Anderson et al., 1997).

ACT-R posits that learning complex skills involves learning the right declarative knowledge chunks and generating the right production rules in the right order as well as practicing deploying the knowledge chunks by way of production rules in the context of solving problems (Anderson, 1996; Anderson et al., 1997). ACT-R also sees an additional knowledge set brought to bear when solving a problem—the goal module—which governs what individuals aim to do when presented stimulus materials that could prompt multiple actions (Anderson et al., 2004). ACT-R also sees excessive failure as not conducive to learning and thus advocates maximizing successful practice and minimizing opportunities for excessive failure (Koedinger & Aleven, 2007). Ultimately, the goal of ACT-R is that students practice applying content knowledge to problems and, in the process, generate and optimize production rules that govern the application of such declarative knowledge to problems (Aleven, Stahl, Schworm, Fischer, & Wallace, 2003).

2.4.1.2.3 How ACT-R Informs Instruction

The goal of instruction according to ACT-R is to present the right knowledge chunks to students in the right order and provide opportunities for structured practice applying the knowledge chunks in the context of problem-solving (Anderson et al., 1997). Instruction should also minimize the chances for failure and maximize the chances of success (Anderson, 1996; Koedinger & Aleven, 2007). Along this vein, prior to beginning the design of instruction, designers should determine what is to be learned and how (Baker et al., 2007). The material to be learned includes declarative knowledge and production rules by which the declarative knowledge can be applied to problems. But the declarative knowledge is to be transmitted to students, and scaffolding should help students engage in the type of problem-solving practice by which they can generate production rules. Unlike with activity theory, there is usually no premium placed on collaboration, although it should be noted that some intelligent tutoring systems are designed to support collaboration (Diziol, Walker, Rummel, & Koedinger, 2010). Furthermore, there is no need necessarily for an overall problem around which all learning is centered; rather, an intelligent tutoring system may incorporate a sequence of related problems.

Taking a step back from the specifics of ACT-R, one may note that underneath the theory is a positivist mindset: that the reality is out there and known, and instruction should transmit to students what is known about reality. This is true to a certain extent. However, in ACT-R, students generate production rules, and such production rules may not be exactly the same amongst all students. It is important to not fall into the trap of thinking that all positivist traditions are simplistic and harmful to learning; rather, positivist approaches can form a solid cornerstone in science, technology, engineering and mathematics (STEM) education (Matthews, 2004).

2.4.1.2.4 How ACT-R Informs Scaffolding

One of the tenets of ACT-R that most influences the design of scaffolding is the idea that it is best to maximize successful practice and minimize unsuccessful practice. In this way, the exact amount of scaffolding informed by ACT-R often can be modified based on (a) model tracing of students' abilities according to their progress through the systems and success or lack thereof on tasks, and (b) student self-selection of hints (Koedinger & Aleven, 2007). Adjustment based on model tracing attempts to automatically increase or decrease base student support based on the system's estimation of students' current abilities. Adjustment based on self-selection most often involves the provision of hints on next steps or strategies to solve the target problem. Most often, the first time a student requests a hint, the provided hint helps a little, the next hint requested helps even more, and the third hint requested is the bottom-out hint—it tells students what to do (Koedinger & Aleven, 2007).

Next, given that ACT-R focuses on promoting the learning of smaller production rules that govern the application of declarative knowledge chunks, scaffolding in ACT-R is at a fairly small grain size, especially in comparison with scaffolding informed by activity theory (Anderson, 1983; Belland & Drake, 2013). That is, scaffolding focuses on subprocesses that contribute to solving problems, rather than macro-processes. In this way, scaffolding informed by ACT-R leads students step-by-step through a series of sub-strategies that are said to lead to success at solving the target problem (Anderson et al., 1997).

2.4.1.3 Knowledge Integration

There is also much scaffolding that is developed to lead to the type of deep content learning that Marcia Linn called knowledge integration (Linn, 2000). Deep content learning means more than simply being able to recall information, but rather being able to describe it in one's own words and apply it in novel situations (Belland, French, & Ertmer, 2009; Bloom, Englehart, Furst, Hill, & Krathwohl, 1956). Such application in novel situations may happen when individuals attempt to create a model of the new problem; in so doing, they may make reference to their current mental models (Kolodner, 1993; Nersessian, 2008). Having an integrated mental model to which to refer improves reasoning efficiency and the likelihood of successful reasoning (Ifenthaler & Seel, 2013; Johnson-Laird, 2001). Knowledge integration is evidenced by integrated mental models describing how nature works, and the knowledge that the same principles of how nature works apply equally well inside and outside of school (Clark & Linn, 2013; Kali, Orion, & Eylon, 2003; Linn, 2000). Furthermore, students who evidence knowledge integration should be able to apply their integrated mental models to novel problems (Linn, 2000; Linn et al., 2003).

2.4.1.3.1 Theoretical Background

The knowledge integration framework was built off of the knowledge in pieces theory (diSessa, 1988), the anchored instruction framework (The Cognition and Technology Group at Vanderbilt, 1990), situated learning in collaborative groups (Brown & Campione, 1994; Lave & Wenger, 1991), and research that suggests that learning outcomes in science instruction would be best served when one focuses on a smaller number of core concepts (Bierman, Massey, & Manduca, 2006; Eylon & Linn, 1988). These perspectives are explained in the paragraphs that follow.

According to the knowledge in pieces theory, students come to school having developed intuitive theories of how physical objects behave under particular circumstances; some of these mini-theories come close to describing phenomena of interest accurately, while others are farther away from describing said phenomena accurately (diSessa, 1988; Taber, 2008). Such mini-theories are not developed as most theories are—through careful reflection on a variety of observations in light of other research and theories. Rather, they are "abstractions from common experiences"—such as the idea that force can move objects (diSessa, 1988, p. 3). These mini-theories do not together constitute a larger, more comprehensive theory. Furthermore, students do not have the right pieces of knowledge to together explain how physical objects behave in a scientifically accurate way. Some research has suggested that such incomplete mini-theories do not necessarily prompt the teaching of correct information to replace the existing mini-theories (Spada, 1994). Rather, instruction needs to help fill in the gaps in students' knowledge (diSessa, 1988).

In anchored instruction, students' learning is centered in an authentic problem situation, which prompts students to define and pursue learning issues (Bransford, Plants, & Vye, 2003; The Cognition and Technology Group at Vanderbilt, 1990). It was designed to prevent the problem of inert knowledge—knowledge that individuals know and can activate when asked to, but they do not spontaneously do so even when a presented problem warrants it (The Cognition and Technology Group at Vanderbilt, 1990). Anchored instruction seeks to promote broad transfer (Bottge, Rueda, Kwon, Grant, & LaRoque, 2007; The Cognition and Technology Group at Vanderbilt, 1990). Within anchored instruction, student learning is centered around several challenges, defined as mini problems that students need to address. Students are also given tools and information with which the challenges can be addressed. Typically, all information and tools that are needed to address the challenges are contained within the anchored instruction program (The Cognition and Technology Group at Vanderbilt, 1990). Students are encouraged to revisit challenges after they gather feedback from peers and teachers (Bransford et al., 2003; The Cognition and Technology Group at Vanderbilt, 1990).

One of the key tenets of the situated learning theory is that all learning takes place in a context, and that to maximize the potential applicability of new learning, one should ensure that the learning context is similar to the context in which the new content is to be applied (Clancey, 2008; Lave & Wenger, 1991). By first observing and then participating at the edges of authentic work groups, students can gradually engage in legitimate peripheral participation, whereby they can gain the skills necessary to participate fully in the community of practice (Collins et al., 1989; Herrington & Oliver, 2000; Lave & Wenger, 1991). This is important such that learners have the contextual cues to access the schemas they create (Greeno & van de Sande, 2007; Lave & Wenger, 1991).

Much research indicates that science learning outcomes are maximized when science curricula covers a smaller number of concepts at a deep level (Achieve, 2013; Clark, 2000; Duschl, 2008; National Research Council, 2007; Pritchard, Barrantes, & Belland, 2009). Specific learning outcomes to be developed include an understanding of science at a conceptual level (as opposed to a set of declarative facts) (Pritchard et al., 2009), learning of concepts and principles that apply across a variety of STEM fields (Achieve, 2013; National Research Council, 2011), and higher-order thinking skills such as problem-solving (Abd-El-Khalick et al., 2004; Jonassen, 2000, 2011) and argumentation abilities (Belland, Glazewski, & Richardson, 2008; Ford, 2012; Kuhn, 2010).

2.4.1.3.2 How New Skills Are Generated According to Knowledge Integration

According to the knowledge integration framework, educators should endeavor to help students develop integrated mental models with which they can view scientific phenomena (Linn, 2000; Linn et al., 2003). Students come to science class with certain preconceptions about how nature works. Instruction then should not attempt to replace such knowledge, but help students integrate new knowledge about the natural world into their existing mental models (Linn, 2000; Linn et al., 2003). Students should also be guided to and have the opportunity to make sense of multiple, conflicting observations (Clark & Linn, 2013). In this process, they can distinguish among and re-order their preexisting ideas and new ideas that are generated (Clark & Linn, 2013). This can be done when students address a multitude of problems in context, aided by context-specific support (e.g., scaffolding) (Clark & Linn, 2013; Kali & Linn, 2008). In so doing, it is important that students see a variety of cases that conflict with their preexisting ideas related to the topic at hand (Linn, 2000). When they attempt to make sense of how the new cases conflict with their preexisting ideas, they have the potential to move toward knowledge integration (Clark & Linn, 2013; Linn et al., 2003).

2.4.1.3.3 How Knowledge Integration Informs Instruction

A central premise of knowledge integration is that students make observations of the world in a variety of settings, and attempt to use these observations to generate mental models with which they can explain natural phenomena (Linn, 2000). But they struggle to sort out these often conflicting observations without detailed and structured instructional guidance (Kali et al., 2003; Linn et al., 2003). Students who believe that science is an unchanging body of knowledge struggle especially hard to develop integrated knowledge about science (Songer & Linn, 1991). Instruction following the knowledge integration approach includes the following processes: Invitation to articulate existing ideas, provision of normative ideas, invitation to distinguish among preexisting and normative ideas, and invitation to reflect on what was learned (Clark & Linn, 2013). Compared to instruction informed by activity theory, knowledge integration aims for a more highly structured instructional approach (Clark & Linn, 2013; Jonassen & Rohrer-Murphy, 1999; Kali et al., 2003).

Knowledge integration is positivistic to the extent that designers are said to be able to identify the ultimate truth, which then can be communicated to students (Clark & Linn, 2013; Linn, 2000; Matthews, 2004). However, students' preexisting ideas about natural phenomena are treated as valuable pieces of a future mental model, and this is more postmodern (Hlynka, 2012; Solomon, 2000).

2.4.1.3.4 How Knowledge Integration Informs Scaffolding

According to the knowledge integration framework, scaffolding is important insofar as it helps enhance students' mental models of scientific concepts, integrating new content with their preexisting knowledge (Linn et al., 2003). To do this, it is important to elicit prior science ideas from students, help them gain new ideas while addressing problems, and help them to see where the new ideas fit with their preexisting ideas (Chang & Linn, 2013; Clark & Linn, 2013). To promote knowledge integration, it is important to make science accessible, make thinking visible, provide social supports, and promote autonomy (Linn, 2000). One can do this by inviting students to articulate their ideas, providing collaboration tools, providing all of the information and tools students need to solve the problem within the system, and inviting students to reflect on what they have learned.

2.4.1.4 Comparison of Theoretical Foundations

2.4.1.4.1 Assumptions About Learning

First, one notes that each of these theoretical bases have starkly different assumptions about learning. One such difference is in their answers to a persistent philosophical question in education: to what extent should educators define what is to be learned? According to ACT-R (Akhras & Self, 2002; Anderson, 1996) and knowledge integration (Linn, 2000), educators should determine what is to be learned and how learning experiences might be arranged to lead to such learning. While in activity theory there is not the thought that any learning is good learning, still there is not as much of a focus on educators unilaterally determining learning goals and scripting learning activities to inexorably lead to such learning goals (Jonassen & Rohrer-Murphy, 1999; Kozulin, 1986; Leont'ev, 1974). Rather, through their interaction with other individuals and tools, supported by scaffolding, learners develop needed skills. The exact skills that are picked up can vary by learners, their goals, the culture in which they operate, and so forth (Akhras & Self, 2002; Belland & Drake, 2013; Jonassen & Rohrer-Murphy, 1999). This has major implications for the design of scaffolding. When designing intelligent tutoring systems based in ACT-R, one needs to model the knowledge structures that are thought to undergird the target higher-order skill (Aleven et al., 2003; Baker et al., 2007). Similarly, when designing scaffolding grounded in knowledge integration, one needs to model the knowledge structures inherent in the type of sophisticated mental model one is targeting (Kali & Linn, 2008; Linn et al., 2003). However, when designing scaffolding from an activity theory perspective, one needs to model the process by which students would engage with an ill-structured problem, including their individual mental process and how they interact with others (Akhras & Self, 2002; Belland & Drake, 2013). Only then could one consider what type of scaffolding tools could be useful for students in the learning context (Akhras & Self, 2002; Belland & Drake, 2013).

Next, the theoretical bases differ in terms of their view on the granularity of knowledge, or lack thereof. One of ACT-R's central premises is that any skill can be broken down into subskills that can be taught in succession in order to teach the overall skill (Anderson, 1990). This perspective is different from that of activity theory, which views overall skills in a holistic manner, and sees a need to help students develop such skills in their entirety in the context of addressing authentic problems, supported by tools and other individuals (Leont'ev, 2009; Luria, 1976). Comparing knowledge integration with activity theory and ACT-R on granularity of knowledge is not the most productive comparison, as the former and the latter models seek to promote different learning outcomes: integrated mental models versus higher-order thinking skills.

2.4.1.4.2 Goals of Scaffolding

The goals of scaffolding informed by each of these theory bases are influenced by the assumptions of the latter. To help with the explanation of the different theoretical bases, consider the goal of teaching problem-solving skill A. According to activity theory, the goal of instruction is to help learners gain higher-order skills in interaction with others (Leont'ev, 1974, 2009; Roth & Lee, 2007). Thus, instruction should give learners the opportunity to use problem-solving skill A when interacting with other individuals and tools. According to this perspective, a skill such as problem-solving skill A cannot be reduced to smaller components. Thus, students need to meaningfully participate in the performance of the whole skill. Scaffolding can extend learners' skill sets as they engage in the target task in collaboration with other individuals. From an activity theory perspective, scaffolding is a tool with which students can engage in collaborative problem-solving, and, by extension, generate the target, higher-order skill (e.g., argumentation ability; Belland & Drake, 2013; Jonassen & Rohrer-Murphy, 1999). Such scaffolding can promote the enhancement of students' problem-solving abilities (Ge & Land, 2004; Raes, Schellens, De Wever, & Vanderhoven, 2012), argumentation abilities (Aufschnaiter, Erduran, Osborne, & Simon, 2008; Belland et al., 2008; Jeong & Joung, 2007) as well as abilities to apply discipline-specific strategies. It focuses on student goals while engaging in the underlying problem-solving activity and attempts to be in the form that students could perceive of as useful when engaging with the problem. From an activity theory perspective, scaffolding need not be designed to minimize the amount of failure, as it recognizes failure as an event that can promote learning (Reiser, 2004; Simons & Ertmer, 2006).

On the contrary, from an ACT-R perspective, instruction should transmit declarative knowledge that students can practice applying when solving problems; in so doing, students generate production rules, which guide how to perform smaller subskills in sequence to perform the entire target skill (Anderson, 1996). Continuing with the example, scaffold developers working from an ACT-R perspective would think about how to break down problem-solving strategy A into smaller subskills (Baker et al., 2007). Declarative knowledge needed to engage in the subskills would be identified, and would be programmed to be delivered to learners in sequence. Scaffolding would be set up to help learners to apply the declarative knowledge in the context of smaller problems and develop production rules in the process. The idea is that the learner would be able to string together the generated production rules to perform problem-solving strategy A. So scaffolding informed by ACT-R has a smaller grain size: it is designed to help students get the practice they need to generate production rules for declarative knowledge that is the focus of the instruction (Koedinger & Corbett, 2006; Means & Gott, 1988). Such scaffolding would provide the opportunity for students to have successful practice applying the knowledge that the intelligent tutoring system delivered. It would also be designed to minimize failure through the use of multiple methods to determine whether adding or removing scaffolding is necessary, including self-selection of hints and the use of model tracing of students' abilities to inform adding and removing scaffolding (Koedinger & Aleven, 2007; Koedinger & Corbett, 2006).

From a knowledge integration perspective, the goal of instruction is to help learners' existing mental models evolve to reflect more generally accepted scientific theories and perspectives (Davis & Linn, 2000; Linn et al., 2003). The idea is that with more sophisticated mental models, learners would be able to effectively address new problems, an idea with strong support in educational research (Gentner & Stevens, 2014; Ifenthaler & Seel, 2013; Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001). At the same time, knowledge integration does not seek to replace learners' existing conceptions (Linn et al., 2003). Scaffolding designed from a knowledge integration perspective would elicit preexisting knowledge related to the new content to be learned, present new content, and help students to integrate the new content with preexisting knowledge while engaging with a problem (Chang & Linn, 2013; Clark & Linn, 2013).

Strategies deployed by scaffolding centered on each of these theory bases would vary as well. Scaffolding grounded in activity theory would tend to incorporate strategies that are highly valued in the target culture, given the importance of cultural knowledge from an activity theory perspective (Engeström, 2009; Leont'ev, 2009; Luria, 1976). Such strategies would not necessarily be designed to produce student success in the fastest manner possible, but to promote meaningful engagement in the problem (Belland & Drake, 2013). Scaffolding grounded in ACT-R would tend to be designed to promote student success as quickly as possible, as ACT-R posits struggle as an impediment to learning (Anderson et al., 1997; Self, 1998). Scaffolding designed from a knowledge integration perspective would aim to activate prior knowledge and promote the acquisition of new knowledge and the integration of new knowledge with existing knowledge (Clark & Linn, 2013; Davis & Linn, 2000).

2.4.1.4.3 Operationalization of Scaffolding

As the goals of scaffolding differ depending on the theoretical framework that undergirds their design and use, so does the operationalization of scaffolding. From an activity theory perspective, stretching students' abilities to the maximum potential is desired (Jonassen & Rohrer-Murphy, 1999; Roth & Lee, 2007). As such, one designs scaffolding so as to maximize productive struggle (Belland, 2014; Reiser, 2004; Simons & Ertmer, 2006). Productive struggle refers to struggle within the areas of the task that are most likely to lead to target learning outcomes and which is not likely to lead to disengagement (Belland, Kim, et al., 2013). Thus, within reason, struggling is not cause for concern, but rather represents an opportunity for learning. In this way, adding scaffolding is not desirable, but rather removing (fading) scaffolding is (Pea, 2004).

From an ACT-R perspective, struggle is counterproductive, and thus intelligent tutoring systems allow students to request hints when they struggle (Anderson et al., 1997; Koedinger & Aleven, 2007). The first hint is more subtle, but as the student requests more, the hints become more direct, eventually ending in a bottom-out hint that provides the answer (Koedinger & Aleven, 2007; Koedinger & Corbett, 2006).

Thus, intelligent tutoring systems leave less latitude for choice in problem-solving direction and action than does scaffolding informed by activity theory.

From a knowledge integration perspective, the goal of scaffolding is to help students fill in gaps in their existing mini-theories about how nature works (Clark & Linn, 2013; Linn, 2000). As such, the promotion of productive struggle is not particularly important. But, at the same time, struggle is not something to be avoided at all costs.

2.4.1.4.4 The Role of the Teacher

Theory and empirical evidence indicates that computer-based scaffolding informed by activity theory and knowledge integration does not work without the provision of one-to-one scaffolding by teachers (Davis & Linn, 2000; McNeill & Krajcik, 2009; Muukkonen et al., 2005; Puntambekar & Kolodner, 2005; Saye & Brush, 2002). Through one-to-one scaffolding, teachers do things like press for understanding and question student understanding, actions for which human teachers are much more suitable than computer-based scaffolding, or at least computer-based scaffolding as informed by activity theory and knowledge integration (Middleton & Midgley, 2002; Pressley, Gaskins, Solic, & Collins, 2006). Meanwhile, computer-based scaffolding can help with tasks for which automated computer tools are better suited, such as persistent support related to important concepts and strategies that figure into the problem solution (Belland, Gu, et al., 2013; Muukkonen et al., 2005; Saye & Brush, 2002).

Often, intelligent tutoring systems are meant to be largely self-contained learning systems, in which computer-based scaffolding engages in some of the questioning of student understanding that is otherwise reserved for human teachers (Koedinger & Aleven, 2007; Koedinger & Corbett, 2006). In these cases, teachers are still important, but their role is more as someone to help smaller number of students who continue to struggle even while using the intelligent tutoring system (Diziol et al., 2010; Koedinger & Corbett, 2006). However, there are intelligent tutoring systems that posit a more active role for the teacher in suggesting the types of help that students seek and planning instruction (Ainsworth, Grimshaw, & Underwood, 1999; Dimitrova & Dicheva, 1998).

2.4.2 Design of Computer-Based Scaffolding

Computer-based scaffolding needs to be designed and developed before target students use it (Belland, 2014). At a global level, this design process can involve thoroughly understanding the process/skill to be promoted (Murray, 1999; Quintana, Krajcik, & Soloway, 2003), predicting the difficulties that target students will face in the task (Baker et al., 2007; Quintana et al., 2003), determining smaller subskills that are involved in the target skill (Koedinger & Aleven, 2007), considering the situations in which the tool will be used (Akhras & Self, 2002; Belland & Drake, 2013), and designing strategies to help students overcome difficulties to assume expertise on the underlying process/skill (Quintana et al., 2003). For example, a scaffold designer may need to carefully define what it means to be an expert related to a particular task and define the gap in expertise between experts and the target learners (Baker et al., 2007; Murray, 1999; Quintana et al., 2003). As part of this process, it is important to determine which elements of the gap are the most difficult for students to overcome. One can do this through difficulty factors analysis—an empirical technique in which the designer varies different task elements in an effort to determine which is the most difficult (Baker et al., 2007). Designers also need to consider the information, activity, management, and reflection needs that learners will face when engaging in the target activity (Quintana et al., 2003). It is important to think about not only the strategies that will be embedded in the scaffolding software, but also about the physical manifestation of these strategies (Quintana et al., 2003). One also needs to consider the types of situations in which learners will use the proposed scaffold—with whom they interact, what they do, and what needs they face (Akhras & Self, 2002; Belland & Drake, 2013).

The design process can vary based on the underlying type/tradition of scaffolding (e.g., scaffolding embedded in intelligent tutoring systems, computer-based scaffolds to support knowledge integration). For example, in the first stage of the design of intelligent tutoring systems, many designers classify target skills in terms of production rules and declarative knowledge (Baker et al., 2007; Koedinger & Corbett, 2006; Murray, 1999). In the initial stages of designing scaffolding to support knowledge integration, defining the content to be learned, and how it might be most productively organized in a mental model, is key (Clark & Linn, 2013; Linn et al., 2003). Furthermore, it is important to consider the existing knowledge target learners will bring to the learning task (Linn et al., 2003). For scaffolding designed according to the activity theory perspective, it is important to characterize the target skill in a holistic manner and consider the types of situations in which students can gain the skill and what support would be needed to enable productive interaction with others in the completion of the task (Akhras & Self, 2002; Belland & Drake, 2013). It is also important to consider the cultural knowledge required to perform the target skill satisfactorily, and how such knowledge can be embedded in the scaffold (Luria, 1976).

2.4.3 Interplay Between Computer-Based and One-to-One Scaffolding

A recent review indicated that technology-based educational innovations are rarely successful unless participating teachers engaged in a sustained professional development program for at least 1 year (Gerard, Varma, Corliss, & Linn, 2011). The reason for this is that with less professional development, teachers are likely to spend most of their time addressing technical problems, and little time helping their students engage in high-level thinking (Gerard et al., 2011). In this way, students do not have the opportunity to benefit from one-to-one scaffolding from their teachers and their learning and performance suffers (Gillies & Boyle, 2006; Maloch, 2002; Raphael, Pressley, & Mohan, 2008).

As noted previously, one-to-one scaffolding and computer-based scaffolding each have unique strengths (see Table 2.1 on page 24). One-to-one scaffolding is the most dynamic form of scaffolding (Chi, 1996; van de Pol et al., 2010; Wood, 2003), more dynamic even than scaffolding in intelligent tutoring systems (Koedinger & Aleven, 2007). One-to-one scaffolding is particularly good at pressing students for understanding and prompting high-level performances (Levpušček, Zupančič, & Sočan, 2013; Middleton & Midgley, 2002; Pressley et al., 2006; Turner et al., 1998). But one-to-one scaffolding is limited in terms of scale and availability in that it requires one teacher to work on a one-to-one basis with one student, a luxury in most K-12 and other classrooms (Belland, 2014; Rodgers, 2004; van de Pol et al., 2010). Because teachers cannot work one-to-one with all students in their class at the same time, it is important to also provide computer-based scaffolding to share the scaffolding load (Belland, 2014; Belland, Gu, et al., 2013; Saye & Brush, 2002). Computer-based scaffolding is available all the time to all students. It also has infinite patience, which can occasionally be an issue with one-to-one scaffolding. By thoroughly designing computer-based scaffolding ahead of students' engagement in learning activities, one can also avoid the possibility of scaffolding messages being provided in qualitatively different ways to different student subgroups (Mertzman, 2008).

One-to-one scaffolding can make computer-based scaffolding more effective by reinforcing themes and pressing students to (a) consider the central problem and the learning material critically, and (b) question their own understanding (Belland, Gu, et al., 2013; Gerard et al., 2011; McNeill & Krajcik, 2009; Muukkonen et al., 2005; Puntambekar & Kolodner, 2005). The synergy afforded by pairing strong computer-based scaffolding with effective one-to-one scaffolding can promote high levels of achievement among students (Belland, Burdo, et al., 2015; McNeill & Krajcik, 2009; Tabak, 2004).

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Chapter 3
Context of Use of Computer-Based Scaffolding

Abstract The contexts in which computer-based scaffolding is used can vary widely. Such variation is by learner population (e.g., grade level and other characteristics such as achievement level and socioeconomic status), subject matter (i.e., science, technology, engineering, and mathematics), and instructional model with which scaffolding is used (e.g., design-based learning and problem-based learning). I describe these variations, and note accompanying variations in effect size estimates. Notably, scaffolding had its strongest impact when students were (a) at the adult level, (b) engaged in project-based learning or problem solving and (c) from traditional learner populations.

Keywords Case-based learning · Context of use · Design-based learning · Education level · Education population · Grade level · Instructional model · Inquiry-based learning · Modeling/visualization · Problem-based learning · Problem-centered instruction · Project-based learning · STEM discipline · Student demographics

3.1 Rationale for this Chapter

To begin this chapter, it is important to discuss the need for a consideration of the context of use of computer-based scaffolding. After all, in its original definition, scaffolding was provided on a one-to-one basis to toddlers who engaged in unstructured problem-solving (Wood, Bruner, & Ross, 1976). All structure to the problem-solving activity was provided by the scaffolding process itself. This was practical when there was one teacher for each student, but lost its practicality as a single source of support when using scaffolding in formal schooling. After all, when a teacher can work on a one-to-one basis with one student for an unlimited time span, the teacher can continually assess what structure is needed, and provide it. This is hard to beat in terms of effectiveness. But in formal school settings, teachers very rarely have this opportunity. So, as researchers turned their attention to how instruction could be centered on problem-solving in formal education, it was important to think about additional ways to provide structure to student learning in

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this context (Palincsar & Brown, 1984; Schmidt, Rotgans, & Yew, 2011). This was often accomplished by pairing scaffolding with formal problem-centered instructional models (e.g., inquiry-based learning and problem-based learning; Crippen & Archambault, 2012; Hmelo-Silver, Duncan, & Chinn, 2007; Kolodner et al., 2003). Such formal, problem-centered instructional models needed to be paired with support for students' reasoning abilities, and instructional scaffolding (one-to-one and, later, computer-based and peer scaffolding) fit such a need nicely.

A natural question is whether the specific problem-centered instructional model with which scaffolding is used influences scaffolding's efficacy. This is an empirical question. It is beyond the scope of this book to investigate variations in the efficacy of one-to-one scaffolding and peer scaffolding based on the specific problem-centered instructional model with which it is used. But I do investigate how the efficacy of computer-based scaffolding varies based on the problem-centered instructional model with which it is used.

Deploying scaffolding in formal education environments also entailed an expansion of the age groups with which scaffolding was used. Computer-based scaffolding is now used among learner populations at the elementary school, middle school, high school, university, graduate school, and adult levels. It is natural to question whether an instructional approach that was originally designed for toddlers, and then modified to allow it to be delivered via a computer-based tool, would be efficacious among these new learner populations, and how the efficacy compares among the different learner groups. This is again an empirical question.

Along with age/grade level, it is also important to consider the area of STEM in which scaffolding was used. Computer-based scaffolding is used in science, technology, engineering, and mathematics education. Is scaffolding more effective when used in the context of one of the STEM disciplines than the remaining STEM disciplines? This is an empirical question that I address in this chapter.

Another important empirical question related to the expansion of the scaffolding metaphor to formal education is whether the efficacy of scaffolding varies depending on the specific characteristics of the learners who use it. For example, does the influence of scaffolding vary according to prior achievement, socioeconomic status (SES), or other factors? Some research suggests that it does (Belland, 2010; Belland, Glazewski, & Richardson, 2011; Belland, Gu, Armbrust, & Cook, 2015; Cuevas, Fiore, & Oser, 2002). Knowing the answer to this question would help scaffolding researchers know where further research is needed to improve outcomes among all students, an important goal to ensure that STEM is for all students (Lynch, 2001; Marra, Peterson, & Britsch, 2008; National Research Council, 2007).

In the next sections, I first discuss research on computer-based scaffolding with an eye on grade level of the learner population, and then summarize the results of meta-analysis regarding differences in effect sizes of scaffolding according to grade level. Next, I discuss variations in the use of scaffolding according to STEM discipline, and differences in effect sizes on that basis. Subsequently, I discuss scaffolding literature in light of student demographics, and then note meta-analysis findings regarding differences in scaffolding's effect according to student demographics. Next, I discuss how scaffolding is used in the context of different problem-centered instructional approaches, and note any according variations in scaffolding's effectiveness.

3.2 Grade Level

In a large expansion from the original grade level among which instructional scaffolding was used in its original conceptualization—preschool (Wood et al., 1976)—scaffolding has come to be used at the primary, middle, secondary, college, graduate, and adult levels (see Fig. 3.1). This likely makes sense in light of Adaptive Character of Thought-Rational (ACT-R) theory, which does not limit the scope of learners with whom it concerns itself. But this also makes sense in light of activity theory. While one traditionally may associate activity theory with learning among the pre-K-12 population, it is clear that the founders of activity theory never intended such a limitation in scope (Leont'ev, 1974; Luria, 1979). Rather, much of the core empirical research supporting activity theory involved adult populations (Luria, 1976). And the idea that one learns in interaction with others, in part by assimilating cultural knowledge, resonates with much other research on adult learning (Coryell, 2013). One may find the most clear such delimitation of a scaffolding-related learning theory in knowledge integration, which generally focuses on the learning of K-12 students (Linn, 2000). However, research from the knowledge integration tradition has been applied to older populations, and it is clear that there is a need for integrated mental models at all levels of education, and that many students at the college, graduate, and adult levels lack this (Ifenthaler & Seel, 2013; Johnson-Laird, 2001).

At the same time, one would be remiss to think that adults and elementary school students, for example, would respond in exactly the same way to computer-based scaffolding. Computer-based scaffolding used among these different populations often varies to a great extent, but sometimes researchers use the same scaffolding for distinctly different student populations, such as graduate and middle school

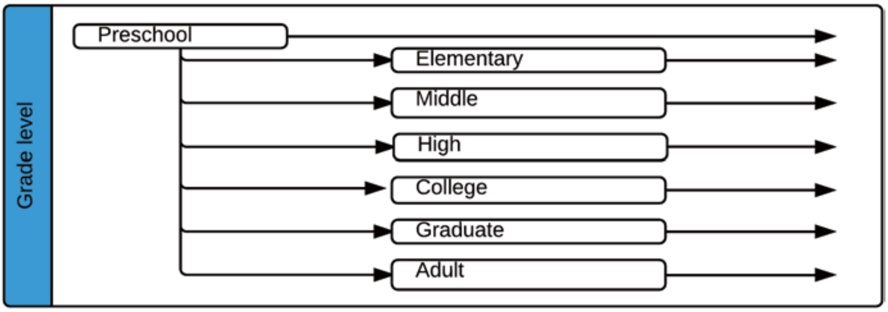

Fig. 3.1 The expansion of grade levels with which scaffolding is used from its original context of use (preschool)

students (Fretz et al., 2002; B. Zhang, Liu, & Krajcik, 2006) or college and middle school students (Kyza & Edelson, 2005; Land & Zembal-Saul, 2003).

It is natural to question whether scaffolding has an effect of similar magnitude among learners at different grade levels.

3.2.1 Results from the Meta-Analysis

The scaffolding meta-analysis (Belland, Walker, Kim, & Lefler, In Press) included outcomes from the following levels: primary ($n_{outcomes} = 28$), middle ($n_{outcomes} = 108$), high school ($n_{outcomes} = 53$), college ($n_{outcomes} = 132$), graduate school ($n_{outcomes} = 11$), and adult ($n_{outcomes} = 1$) (See Table 3.1). Scaffolding had a statistically significantly greater effect among adult learners than among college learners, high school students, middle level students, and primary students, $p < 0.01$. Caution is warranted as the effect size estimate for adult learners is based on one outcome. Still, this is intriguing, in that one might have ventured to guess that the effect would be lowest among adults, given that scaffolding was originally developed for use among toddlers. At the same time, it is important to recall that in its original definition, instructional scaffolding referred to one-to-one interactions (Wood et al., 1976).

Due to the higher sample size of effect sizes among middle level students than among graduate level learners, the 95 % confidence interval for scaffolding's effect among middle level learners (0.29–0.46) was tighter than it was for scaffold's effect among adult learners (0.20–1.52). Thus, the true effect size for adult learners may be lower than 0.86. From an activity theory perspective, scaffolding aims to help learners gain the cultural knowledge that helps to solve target problems effectively (Belland & Drake, 2013; Jonassen & Rohrer-Murphy, 1999). This is certainly something that graduate students and adults need to do. Still, the exact reason the effect size estimate is significantly greater among adult learners than among other age groups is unclear.

It is important to recall that the fact that scaffolding had a statistically significantly greater effect among adult learners than among students from other age groups

Table 3.1 Table of results of moderator analyses on the effect of education level on cognitive outcomes

Level	*n* outcomes	Effect size estimate	95 % Confidence interval	
			Lower limit	Upper limit
Adult	1	0.86	0.20	1.52
Graduate	11	0.61	0.22	1.00
College	132	0.49	0.42	0.57
High school	53	0.48	0.34	0.62
Middle school	108	0.37	0.29	0.46
Elementary	28	0.55	0.40	0.67

does not mean that scaffolding's effect was negative or inconsequential among the latter. Indeed, the effect size estimates of scaffolding used by elementary, middle, high school, college, and graduate level learners range from 0.37 to 0.61, which is above the threshold suggested for practical significance (Gall, Gall, & Borg, 2003), is substantially larger than the average effect of educational technology interventions for mathematics education ($ES=0.16$; Cheung & Slavin, 2013), and is significantly greater than zero. Furthermore, it is similar to the average effect of interventions designed to enhance critical thinking abilities among a wide range of learners ($ES=0.341$; Abrami et al., 2008), and higher than that of interventions designed to enhance critical thinking abilities among college students ($ES=0.195$; Niu, Behar-Horenstein, & Garvan, 2013). In short, scaffolding led to effect sizes that were significantly greater than zero, and practically significant, among individuals at the elementary, middle, secondary, college, graduate, and adult levels. For one intervention to be so robust to differences in student populations, and to so uniformly lead to positive effects, is rare in educational research.

One may ask if the scaffolding interventions in the included research were similar enough to all be called scaffolding. The lack of precision in the term scaffolding that had emerged throughout its expansion has been widely lamented (Pea, 2004; Puntambekar & Hübscher, 2005). The scaffolding definition that guided the underlying meta-analysis was

> Support that assists students as they generate solutions to complex and ill-structured tasks, problems, or goals, and increases and helps students integrate higher-order competencies, including problem solving skills, deep understanding of content (knowledge integration), or argumentation.

This definition was applied strictly. For example, articles in which the intervention was given to students before they engaged in the problem were excluded, as were articles in which students were not addressing authentic, ill-structured problems or tasks. But there is clearly room for variation in the scaffolding interventions provided that they met the scaffolding definition.

3.3 STEM Discipline

Though STEM content was not central to the original instructional scaffolding definition (See Fig. 3.2), scaffolding has grown to be a central instructional strategy used in conjunction with problem-centered instruction in STEM education (Crippen & Archambault, 2012). The problem-centered instructional models used in each of these disciplines often vary. For example, modeling/visualization tends to be used most often in engineering and mathematics education (Lesh & Harel, 2003; Vreman-de Olde & de Jong, 2006). Design-based learning tends to be used most often in engineering education or in science education integrated with engineering content (Gómez Puente, Eijck, & Jochems, 2013; Kolodner et al., 2003; Mehalik, Doppelt, & Schuun, 2008). Problem-based learning is often used in science and en-

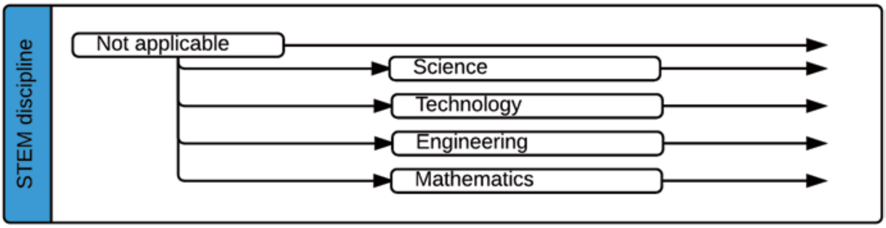

Fig. 3.2 The expansion of disciplines of instruction in which scaffolding is used, going from non-STEM to science, technology, engineering, and mathematics

gineering education (Belland, 2010; Carr, Bennett, & Strobel, 2012; Hmelo-Silver, 2004). Furthermore, the types of skills being supported and content being developed varies among the disciplines. For example, design-based learning is prominent in engineering education because engineering places such a strong emphasis on the design of solutions to address problems.

3.3.1 *Results from the Meta-Analysis*

Outcomes from science ($n_{outcomes} = 208$), technology ($n_{outcomes} = 51$), engineering ($n_{outcomes} = 30$), and mathematics education ($n_{outcomes} = 44$) were included (See Table 3.2; Belland et al., In Press). Results indicate that there was no difference in scaffolding's effect on the basis of discipline. This suggests that scaffolding is a robust intervention that is highly effective when used solving problems in a variety of subject matters.

3.4 Student Demographics

The original scaffolding description was developed among traditional, middle class students (See Fig. 3.3; Wood et al., 1976). In the scaffolding literature, one often sees variations in cognitive outcomes from scaffolding based on student factors such as achievement level, SES, and other factors associated with underrepresenta-

Table 3.2 Table of results of moderator analyses on the effect of STEM discipline on cognitive outcomes

Level	*n* outcomes	Effect size estimate	95 % Confidence interval	
			Lower limit	Upper limit
Science	208	0.42	0.36	0.48
Technology	51	0.51	0.36	0.67
Engineering	30	0.58	0.42	0.73
Mathematics	44	0.54	0.42	0.65

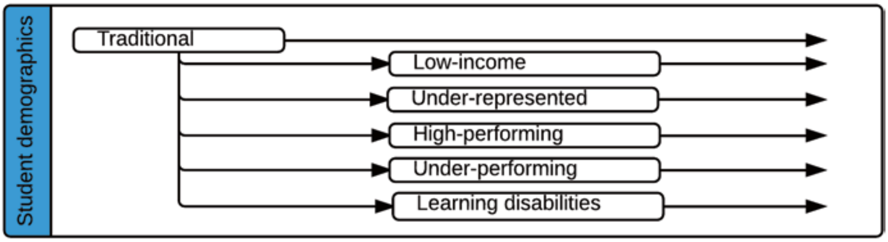

Fig. 3.3 The expansion of student populations with which instructional scaffolding is used, from traditional to traditional, low-income, underrepresented, high-performing, underperforming, and student with learning disabilities

tion in STEM (Azevedo, Winters, & Moos, 2004; Belland, 2010; Belland et al., 2011; Belland, Gu, Armbrust, et al., 2015; Belland, Gu, Kim, Turner, & Weiss, 2015; Cuevas et al., 2002; Simons & Klein, 2006). It is important to investigate the extent to which scaffolding's influence varies according to these variables to guide future scaffolding research and development, so as to help ensure that STEM is for all (Lynch, 2001; National Research Council, 2007).

3.4.1 *Results from the Meta-Analysis*

Outcomes from the following learner populations were included: traditional ($n_{outcomes} = 279$), low income ($n_{outcomes} = 11$), underrepresented ($n_{outcomes} = 17$), high-performing ($n_{outcomes} = 8$), and underperforming ($n_{outcomes} = 18$) (See Table 3.3; Belland et al., In Press). Students from traditional learner populations had a statistically significantly higher average effect size ($g = 0.48$) than underperforming students ($g = 0.28$), $p < 0.05$. This is concerning, as it is very important to maximize success opportunities in STEM for students from underrepresented groups (Ceci, Williams, & Barnett, 2009; National Research Council, 2011; Thoman, Smith, Brown, Chase, & Lee, 2013). Further research is needed to examine how to design and deploy computer-based scaffolding so as to increase its efficacy among underrepresented groups. There may also be a need to develop versions of scaffolds that draw on strategies known to be effective among the underrepresented groups (Cuevas et al., 2002; Lynch, 2001; Marra et al., 2008). It is clear from the literature that this is possible, as some studies have shown that specific scaffolds are more effective among lower-achieving and lower-SES middle school students than among higher-achieving and average-to-higher-SES students (Belland et al., 2011; Belland, Gu, Armbrust, et al., 2015; Belland, Gu, Kim, et al., 2015).

Table 3.3 Table of results of moderator analyses on the effect of student demographics on cognitive outcomes

Level	*n* outcomes	Effect size estimate	95 % Confidence interval	
			Lower limit	Upper limit
High performing	8	0.36	0.07	0.66
Low income	11	0.51	0.32	0.70
Traditional	279	0.48	0.42	0.53
Underperforming	18	0.28	0.12	0.45
Underrepresented	17	0.41	0.17	0.66

3.5 Instructional Model with Which Scaffolding is Used

In the original formulation of the scaffolding definition, no thought was given to the instructional model with which scaffolding was used, as it was centered on one-to-one tutoring of toddlers learning to build pyramids with wooden blocks (Wood et al., 1976). But as scaffolding was applied to formal education, one needed to consider the problem-centered instructional model with which scaffolding would be used (See Fig. 3.4). Scaffolding can be used in the context of such instructional strategies as problem-based learning, case-based learning, design-based learning, inquiry-based learning, project-based learning, and other instructional approaches that engage students in problem-solving. It is natural to question whether scaffolding's effectiveness varies according to the problem-centered instructional model with which it is used. There is reason to believe that it may, because different problem-centered models have different levels of structure and support for students built into their approach. The underlying support of the instructional model could interact with the support of scaffolding in a positive or negative way.

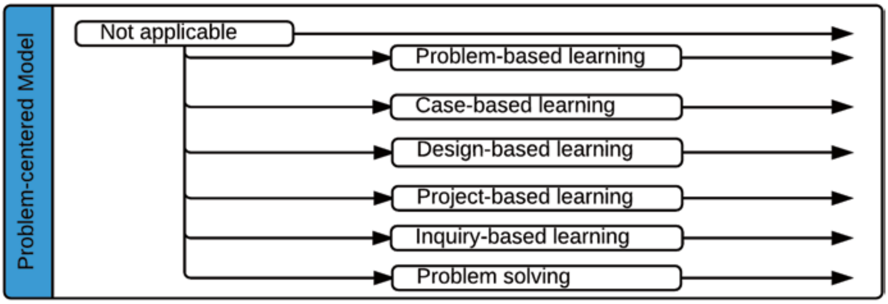

Fig. 3.4 The expansion of formal, problem-centered models with which to use instructional scaffolding, from none to problem-based learning, case-based learning, design-based learning, project-based learning, inquiry-based learning, and problem-solving

3.5.1 Problem-Based Learning

Problem-based learning is an instructional approach in which students are presented with an authentic, ill-structured problem, and need to determine what they already know about the problem and what they need to know (learning issues; Barrows & Tamblyn, 1980; Hmelo-Silver, 2004). Typically, teachers present a driving question such as, "How does water quality affect the flora and fauna of X valley?" to which students can refer throughout the unit, and which reminds them of the fundamental reason they are addressing the problem (Ertmer & Simons, 2006). After being presented with the problem, defining it, and generating learning issues, students proceed to address their learning issues, and then develop a potential solution and back it up with evidence (Belland, Glazewski, & Richardson, 2008; Hmelo-Silver, 2004). They then need to defend their solution (Belland et al., 2008).

Originally developed in the medical school context, problem-based learning is still used extensively there (Barrows & Tamblyn, 1980; Gijbels, Dochy, Van den Bossche, & Segers, 2005; Kalaian, Mullan, & Kasim, 1999). In this setting, simulated patients often present with an unidentified illness, and students need to research what might cause such symptoms, triangulate such with test results, and propose a diagnosis and treatment (Barrows, 1985; Hmelo et al., 2001). Problem-based learning is also used in other university contexts such as business (Arts, Gijselaers, & Segers, 2002; Giesbers, Rienties, Tempelaar, & Gijselaers, 2013) and teacher education (Hmelo-Silver, Derry, Bitterman, & Hatrak, 2009; McCormick Peterman, 2012), as well as in various K-12 contexts. For example, in high school social studies, students addressed historical problems in the civil rights era (Saye & Brush, 2002). Middle school science students addressed a problem related to genetic testing and its relationship with such issues as medical insurance and public health (Belland, 2010; Belland et al., 2011). Furthermore, middle school students addressed the evolution of water quality in a local river, and what should be done about it (Belland, Gu, Armbrust, et al., 2015; Belland, Gu, Kim, et al., 2015). College statistics students investigated the extent to which claims related to a presented problem were supported by statistics (Karpiak, 2011). Preservice teachers investigated typical classroom problems, and developed solutions using educational psychology content (Hmelo-Silver et al., 2009). In these settings, problems are often presented through text-based or video-based synopses of the problem (Hmelo-Silver, 2004; Hung, Jonassen, & Liu, 2007).

In problem-based learning, students most often work in small groups. Though the sizes of the groups sometimes vary, 3–4 students is often posited as an ideal size in terms of promoting maximum student discussion (Arts et al., 2002; Lohman & Finkelstein, 2000). Different members of groups often perform different roles based on their individual strengths, and this can serve to extend each student's capabilities (Belland, Glazewski, & Ertmer, 2009; Helle, Tynjälä, & Olkinuora, 2006). However, there is some evidence that problem-based learning can be effective even when students work individually (Pease & Kuhn, 2011).

Problem-based learning both requires the use of strong self-regulated learning skills on the part of students, and can often lead to the enhancement of self-regulated learning skills (Evensen, Salisbury-Glennon, & Glenn, 2001; Loyens, Magda, & Rikers, 2008). But it also requires that students identify learning issues related to what they need to know to solve the problem (Hmelo-Silver, 2004; Loyens et al., 2008). Many K-12 students lack sophisticated self-regulated and self-directed learning skills and so need to be supported in these areas through scaffolding (Azevedo, 2005; Loyens et al., 2008). Similar struggles with self-directed learning can be seen among college students (Lekalakala-Mokgele, 2010) and medical students (Lohman & Finkelstein, 2000). Perhaps due to problem-based learning's focus on self-regulated learning, being exposed to problem-based learning and accompanying one-to-one scaffolding led seventh grade science students to develop significantly and substantially more enhanced epistemic beliefs (Belland, Gu, Kim, et al., 2015).

Problem-based learning leads to strong learning outcomes. For example, meta-analyses indicate that problem-based learning has a strong effect on principles-level (Gijbels et al., 2005) and application-level (Walker & Leary, 2009) outcomes and long-term retention (Strobel & van Barneveld, 2009). At the principles level, students performed on average 0.795 standard deviations better than their control counterparts (Gijbels et al., 2005). The advantage at the application level was 0.334 standard deviations (Walker & Leary, 2009). Given that the Strobel and van Barneveld's (2009) paper was a meta-synthesis, a quantitative estimate of the effect size difference is not available. Problem-based learning has often been found to lead to weaker immediate recall than lecture (Albanese & Mitchell, 1993; Dochy, Segers, Van den Bossche, & Gijbels, 2003; Kalaian et al., 1999) but better long-term retention and deep content learning than lecture (Belland, French, & Ertmer, 2009; Pourshanazari, Roohbakhsh, Khazaei, & Tajadini, 2013; Strobel & van Barneveld, 2009).

3.5.2 Case-Based Learning

Case-based learning is often used in the law school and business school contexts. But it also has been used in such STEM disciplines as medicine (Thistlethwaite et al., 2012) and physics (J. Zhang, Chen, Sun, & Reid, 2004). Lectures on the necessary content to understand the case often precede the presentation of cases. The premise is that by providing cases, instruction can help students build up a repertoire of cases upon which learners can draw when encountering similar problems in the future (Jonassen & Hernandez-Serrano, 2002; Kolodner, 1993). Cases can also provide concrete contexts in which the new content can be applied. Cases can represent a business transition or response to a problem or a particularly cogent legal case/argument/decision. Cases are often presented in a group discussion context, but can also take the form of a video summary or an online case presentation (Thistlethwaite et al., 2012). In it, learning content to be covered in the case (often via listening to a lecture) happens before students engage with the case. Typically, there is not much content to be learned after being presented with the case, but rather students need to reason based on what they have already learned (Srinivasan, Wilkes, Stevenson, Nguyen, & Slavin, 2007). Furthermore, faculty give students more active guidance than they would in a problem-based learning approach (Srinivasan et al., 2007). In this way, on the continuum of problem-centered approaches to instruction, case-based learning is closer to the more guided side than to the less guided side (Srinivasan et al., 2007). While cases represent authentic problems, they are typically more context bound than problem-based learning problems (Jonassen, 2000; Savery, 2006). In addition, cases are used to assess learning and promote application, rather than to drive learning (Savery, 2006).

The relative sophistication of students' epistemic beliefs influence their ability to perform well in a case-based learning environment, with students with sophisticated epistemic beliefs performing better and benefitting more from scaffolding than students with unsophisticated epistemic beliefs (Demetriadis, Papadopoulos, Stamelos, & Fischer, 2008; Peng & Fitzgerald, 2006). Some evidence indicates that case-based instruction can also help students develop more sophisticated epistemological beliefs (Çam & Geban, 2011).

Systematic reviews of the literature on the use of case-based learning in medical education indicates that students and instructors like the method very much, but how its impact on learning compares with that of other methods is not conclusive (Srinivasan et al., 2007; Thistlethwaite et al., 2012).

3.5.3 Design-Based Learning

In design-based learning, students are presented with an authentic, ill-structured problem, but rather than develop a conceptual solution, they need to design/engineer a product that addresses the problem (e.g., a levee to prevent erosion on a barrier island (Kolodner et al., 2003), an alarm to address a problem that students identified (Silk, Schunn, & Cary, 2009)). Such problems are usually drawn from students' immediate communities, and students often have an opportunity to identify a specific subproblem on which they want to work (Doppelt & Schunn, 2008; Duran, Höft, Lawson, Medjahed, & Orady, 2014). The central problem in this approach is often termed a design challenge (Brophy, Klein, Portsmore, & Rogers, 2008). To address design challenges, it is important to consider the goals as envisioned by various project stakeholders, as well as constraints governing the design of a solution (Brophy et al., 2008). For example, design challenges can include preventing erosion on barrier islands and designing a model car that can go up and down hills on a track (Kolodner et al., 2003). In another approach to design-based learning, students generate a design challenge related to security alarms, taking into account where they personally need an alarm system (e.g., to remind someone to take medicine or to alert that something has been stolen (Doppelt, Mehalik, Schunn, Silk, & Krysinski, 2008)). In the process of designing the product, students need to address learning issues (Chandrasekaran, Stojcevski, Littlefair, & Joordens, 2013; Kolodner et al., 2003; Silk et al., 2009).

To my knowledge, the effect of design-based learning has not been investigated through meta-analysis. But individual empirical studies indicate that design-based learning leads to many beneficial outcomes. For example, middle school students engaged in design-based learning have been found to learn science content and problem-solving skills more effectively than typical instruction controls (Kolodner et al., 2003) and gain substantially in science inquiry skills from pre to post (Silk et al., 2009). Furthermore, design-based learning led to significant increases in content knowledge and core STEM process skills among high school students (Duran et al., 2014).

3.5.4 Inquiry-Based Learning

Inquiry-based learning is characterized by overt foci on students (a) posing their own questions early in the process (Edelson, Gordin, & Pea, 1999) and (b) designing and carrying out an experimental technique to address the generated questions (Abd-El-Khalick et al., 2004; Gibson & Chase, 2002). In this way, inquiry-based learning differs markedly from the "rhetoric of conclusions" approach to science labs used in many science classes, in which students are presented a question for which scientists know the answer quite well and given experimental procedures to follow to address that question (Chinn & Malhotra, 2002; Duschl, 2008). Rather, in inquiry-based learning, students need to identify variables, state hypotheses, design and carry out tests of those hypotheses, and interpret and explain the results (Edelson et al., 1999; Jong, 2006; Minner, Levy, & Century, 2010). There is substantial guidance from teachers and technology along the way, for example, for identifying pertinent variables and formulating testable hypotheses (Jong, 2006; Keys & Bryan, 2001). For example, high school students were invited to interact with a climate visualization, in which they could identify questions they wanted to address and manipulate variables to see how that affected dependent variables (Edelson et al., 1999). In another example, high school students interacted with an astronomy visualization with which they could address ten questions by manipulating variables (Taasoobshirazi, Zuiker, Anderson, & Hickey, 2006).

According to a recent meta-analysis of the literature on inquiry-based instruction in science, the model led to an average effect of 0.5, a medium-large effect (Furtak, Seidel, Iverson, & Briggs, 2012). Notably, the effect sizes in the review were twice as big when teacher support was highest (Furtak et al., 2012). According to another review, it may not be inquiry-based learning per se that leads to strong learning outcomes, but the extent to which students need to analyze authentic data and generate conclusions (Minner et al., 2010).

Examined individually, empirical studies indicate that inquiry-based learning can help students develop inquiry skills, as well as deep content learning (Crippen & Archambault, 2012; Edelson et al., 1999; Marx et al., 2004). Inquiry-based learning can be a good strategy to help students in underperforming districts perform at a higher level, when deployed as part of systematic reform (Marx et al., 2004).

Furthermore, inquiry-based learning can promote enhanced and sustained interest in science (Gibson & Chase, 2002). An extensive review of the inquiry-based learning literature indicated that it may be the extent to which students need to actively think, rather than the model of inquiry-based learning in and of itself, that leads to enhanced content learning (Minner et al., 2010).

3.5.5 Project-Based Learning

In project-based learning, students address a problem, but the central focus is on the product that students need to create (Helle et al., 2006; Krajcik et al., 1998). Some examples of products are a video, a PowerPoint presentation, or a report. In developing project-based learning curricula, designers list academic standards, specify what students should be able to do according to the standard, and devise a performance (project) that would provide evidence of mastery of the skill (Barron et al., 1998; Krajcik et al., 1998). For example, a project-based learning unit in middle school invited students to design blueprints for a playhouse, given a set of donated materials (Barron et al., 1998). Students then work toward the project, which is typically contextualized in some sort of problem that students have the potential to find engaging (Krajcik, McNeill, & Reiser, 2008). As with problem-based learning, a driving question typically guides student learning in project-based learning (Barron et al., 1998). A primary purpose of a driving question in this case is to keep student focus on the content being learned and the issues being addressed, rather than on the project per se (Barron et al., 1998). While the parameters of the project deliverable are given to students at the beginning of the unit, students typically have a substantial amount of freedom in determining the exact features of the deliverable, as well as the route to get there (Helle et al., 2006). However, project-based learning is typically more structured than problem-based learning in that its deliverable is more well-specified (Savery, 2006). At the end of project-based learning, students typically produce the target product, and then engage in some sort of reflection, which can include the creation of a portfolio (Turns, Cuddihy, & Guan, 2010).

Research on project-based learning is often focused more on curricular design than on student learning (Helle et al., 2006). However, an examination of the project-based learning literature can lead one to some observations. First, project-based learning can lead to strong gains in design skills on the part of elementary school students (Barron et al., 1998) and college students (Dym, Agogino, Eris, Frey, & Leifer, 2005). It is also an instructional approach that can be very motivating (Blumenfeld et al., 1991; Helle, Tynjälä, Olkinuora, & Lonka, 2007). However, project-based learning does not necessarily promote motivation in and of itself; rather, designers should take care to design projects so as to enhance and sustain motivation (Blumenfeld et al., 1991) and to design scaffolding that supports motivation (Belland, Kim, & Hannafin, 2013).

3.5.6 Other Instructional Approaches

Scaffolding can be incorporated into other instructional approaches that incorporate authentic problem-solving but do not fit the above labels. This approach will be called *problem-solving instruction* for the purposes of this book. For example, much work in intelligent tutoring systems does not fit within any of the above instructional models, as it is grounded in the ACT-R theory of learning (Anderson, Matessa, & Lebiere, 1997). However, much of it does involve authentic problem-solving. As noted in Chap. 2 (this volume), intelligent tutoring systems focus on delivering knowledge chunks to students that they can then apply to problems that are provided in sequence. Scaffolding within Intelligent Tutoring Systems focuses on helping students apply the content to the problems, and in the process generate production rules. Production rules are defined as rules governing the application of declarative content to problems that can be applied without conscious control to similar problems in the future (Koedinger & Corbett, 2006; Self, 1998).

Many intelligent tutoring systems are used in mathematics. For example, the *Geometry Cognitive Tutor* presents a series of geometry problems along with diagrams (Aleven & Koedinger, 2002). Students need to calculate things like angles and type explanations of how they got their answer. They are given feedback on the basis of their answer and explanations (for the most common mistakes, detailed feedback is provided). Students can also request hints.

3.5.7 Results from the Meta-Analysis

The meta-analysis included outcomes in which scaffolding was used in the context of problem-based learning ($n_{outcomes}=38$), case-based learning ($n_{outcomes}=15$), modeling/visualization ($n_{outcomes}=42$), project-based learning ($n_{outcomes}=5$), design-based learning ($n_{outcomes}=4$), inquiry-based learning ($n_{outcomes}=69$), and problem-solving ($n_{outcomes}=160$) (See Table 3.4; Belland et al., In Press). Results indicated that scaffolding utilized in the context of project-based learning had a higher average effect size ($g=1.33$) than scaffolding used in the context of problem-based

Table 3.4 Table of results of moderator analyses on the effect of problem-centered model on cognitive outcomes

			95 % Confidence interval	
Level	*n* outcomes	Effect size estimate	Lower limit	Upper limit
Case-based learning	15	0.28	0.04	0.53
Design-based learning	4	0.30	−0.12	0.82
Inquiry-based learning	69	0.42	0.33	0.52
Modeling/visualization	42	0.51	0.34	0.68
Problem-based learning	38	0.27	0.11	0.43
Problem-solving	160	0.53	0.45	0.58
Project-based learning	5	1.33	1.03	1.63

learning ($g=0.27$), problem-solving ($g=0.53$), modeling/visualization ($g=0.51$), design-based learning ($g=0.30$), inquiry-based learning ($g=0.42$), and case-based learning ($g=0.28$), $p<0.01$. Furthermore, scaffolding used in the context of problem-solving had a higher effect size estimate ($g=0.53$) than scaffolding used in the context of problem-based learning ($g=0.27$), $p<0.01$. Still, this difference is borderline, as the 95 % confidence intervals overlap.

Of note, most studies that used the "problem-solving" instructional approach involved intelligent tutoring systems informed by the ACT-R theory (Anderson et al., 1997; Corbett & Anderson, 2001; Koedinger & Corbett, 2006). A previous meta-analysis found that step-based intelligent tutoring systems led to an average effect size of 0.76 (VanLehn, 2011), which is considerably larger than the average effect size of computer-based scaffolding from the current, underlying, scaffolding meta-analysis ($g=0.46$). This does not mean that intelligent tutoring systems are superior to other scaffolding types, as they target a different form of learning than other scaffolding types and hold different assumptions about learning and ways to help people learn most effectively. Notably, intelligent tutoring systems are the most highly structured instructional programs that involve scaffolding, in that they carefully script all student actions, and what happens when students do particular actions (Koedinger & Aleven, 2007; Koedinger & Corbett, 2006). The only exception to this is typically the inclusion of a hint button, which students can choose to press or not. It may be that the structure of intelligent tutoring systems in conjunction with scaffolding helps produce effects of a larger magnitude. It is important to note that this inclusion of a very tight structure means that intelligent tutoring systems tend to minimize opportunities for self-directed learning. For further discussion of the theoretical bases of scaffolding, please see Chap. 2 (this volume).

It is notable that the effect size estimate for computer-based scaffolding used in the context of inquiry-based learning ($g=0.42$) is below that of inquiry-based learning found in a recent meta-analysis ($ES=0.50$) by Furtak et al. (2012). However, it is reasonably close. One may imagine that not all studies covered in the latter meta-analysis included computer-based scaffolds. Further research is needed to disentangle the effect of computer-based scaffolding and that of inquiry-based learning in this context.

That the effect size of computer-based scaffolding was lowest when paired with problem-based learning may be explained by the open-ended nature of problem-based learning. Problem-based learning requires self-directed learning perhaps to the greatest extent among the covered problem-centered instructional approaches (Lohman & Finkelstein, 2000; Loyens et al., 2008; Savery, 2006). Problem-based learning students are responsible not only for defining the problem, but also determining what they need to know to come up with a solution, finding the information, and synthesizing the information to determine a solution (Belland et al., 2008; Hmelo-Silver, 2004; Loyens et al., 2008). In short, students have less structure from the inherent nature of problem-based learning than they would have from inquiry-, case-, project-, or design-based learning. Thus, they need to be relatively autonomous. This can be particularly challenging for K-12 students who have little experience with autonomy in school (Jang, Reeve, & Deci, 2010; Rogat, Witham,

& Chinn, 2014; Stefanou, Perencevich, DiCintio, & Turner, 2004). Furthermore, if teachers do not provide appropriate autonomy support, defined as the provision of meaningful choice in academic tasks and explanation when choice is not possible, students may not strive to achieve mastery, but rather, strive to perform better than other students (Ciani, Middleton, Summers, & Sheldon, 2010; Deci & Ryan, 2000). The nature of scaffolding used in the context of problem-based learning is thus uniquely targeted toward the need for students to be self-determined (Belland et al., 2008; Hmelo-Silver et al., 2007).

What problem-based learning students can propose as a solution is typically more open-ended than in case-based learning, project-based learning, design-based learning, modeling/visualization, and inquiry-based learning (Hmelo-Silver, 2004; Savery, 2006). That is, possible deliverables include conceptual solutions to the problem, persuasive presentations, artifacts, or some combination of products. In this way, problem-based learning may be seen as more loosely structured than other problem-centered instructional models (Hung, 2011; Savery, 2006).

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Chapter 4
Intended Learning Outcomes and Assessment of Computer-Based Scaffolding

Abstract In this chapter, I describe the intended learning outcomes of scaffolding—content knowledge and higher-order thinking abilities—and link these to the goals advanced by the Next Generation Science Standards and related documents from recent curricular revisions in STEM education. Furthermore, I address different ways in which scaffolding's effect can be measured (assessment level), and explore whether there are differences in the magnitude of scaffolding's effect according to assessment level. Meta-analysis results show that there is no difference in effect size magnitude on the basis of intended learning outcome (i.e., content knowledge or higher-order thinking abilities). Scaffolding's effect was greater when measured at the principles level than when measured at the concept level. But scaffolding's effect was statistically greater than 0 and substantial for all three assessment levels (i.e., concept, principles, and application). These results are then discussed.

Keywords Application-level assessment · Argumentation · Assessment levels · Common Core · Concept-level assessment · Epistemology · Intended learning outcomes · Next Generation Science Standards · Principles-level assessment · STEM education

4.1 Rationale for this Chapter

In science, technology, engineering, and mathematics (STEM) education, computer-based scaffolding has been deployed to help enhance students' higher-order thinking skills (Belland, 2010; Cho & Jonassen, 2002; Eck & Dempsey, 2002; M. Kim & Hannafin, 2011) and deep content learning (Chang & Linn, 2013; Davis, 2003; Hwang, Shi, & Chu, 2011). These diverse learning outcomes may be seen by some as evidence of two categorically different interventions that cannot be considered alongside each other. But these dual emphases of scaffolding can be seen as congruent with the emphases on learning the process of STEM, as well as learning cross-cutting concepts and disciplinary core ideas in the Next Generation Science Standards (NGSS; Achieve, 2013; National Science Board, 2010). Needless to say, scaffolding's emphases did not emerge in direct response to the writing of the NGSS, as such emphases were formed well before the NGSS existed. Rather, scaffolding's intended learning outcomes arose within and alongside the currents of

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the transformation of education from a didactic process of information transfer to one of construction of knowledge.

In this chapter, to provide context and to help the reader understand the seeming dichotomy of learning goals of scaffolding, I first situate scaffolding relative to the calls for the enhancement of content knowledge and higher-order thinking skills in the NGSS (Achieve, 2013; Krajcik, Codere, Dahsah, Bayer, & Mun, 2014; National Science Board, 2010) and the Common Core State Standards (McLaughlin & Overturf, 2012; National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010).

Second, I expand on the intended learning outcomes of scaffolding. Variation in intended learning outcomes of scaffolding largely aligns with differences in the theoretical underpinnings of scaffolding, which were discussed in Chap. 2: "Instructional Scaffolding: Foundations and Evolving Definition." I also explore if the effectiveness of scaffolding varies according to intended learning outcome, as informed by the meta-analysis results.

Just as it is important to consider intended learning outcomes, it is also important to consider how learning is assessed (Belland, 2012; Belland, French, & Ertmer, 2009; Furtak & Ruiz-Primo, 2008; Messick, 1989). Indeed, one is often advised to consider assessment before even designing objectives and instructional materials/strategies (Gagné, 1965; Wiggins & McTighe, 2005). By considering how scaffolding's influence on cognitive outcomes varies according to how it is assessed—at the concept, principles, or application level (Sugrue, 1995)—one can see if scaffolding as a whole delivers stronger impacts on content learning or various types of higher-order thinking skills. It is important to consider this alongside the intended learning outcome, as (a) just because an intervention is designed to increase content learning or higher-order skills does not necessarily mean that it does, and (b) just because scholars claim that scaffolding is intended to help students enhance their skill in a particular area does not always mean that the learning is being assessed at that level.

In this chapter, I discuss these ideas, and present meta-analysis results comparing scaffolding's impact according to intended learning outcome and assessment levels.

4.2 Targeted Learning Outcomes of Scaffolding

Scaffolding has been designed to promote higher-order skills such as ill-structured problem-solving ability (Ge & Land, 2004; Liu & Bera, 2005) and argumentation ability (Belland, Gu, Armbrust, & Cook, 2015; McNeill & Krajcik, 2009), and enhanced/deep content knowledge (Davis & Linn, 2000; Koedinger & Corbett, 2006). It is important to note that in the intelligent tutoring systems literature, authors posit a focus on enhancing procedural knowledge (production rules) by which individuals can apply declarative knowledge. Some may argue that this is a form of problem-solving skill. But I argue that it is a form of content learning, as each production rule is concerned with how to apply one highly specific domain knowledge element (Anderson et al., 2004).

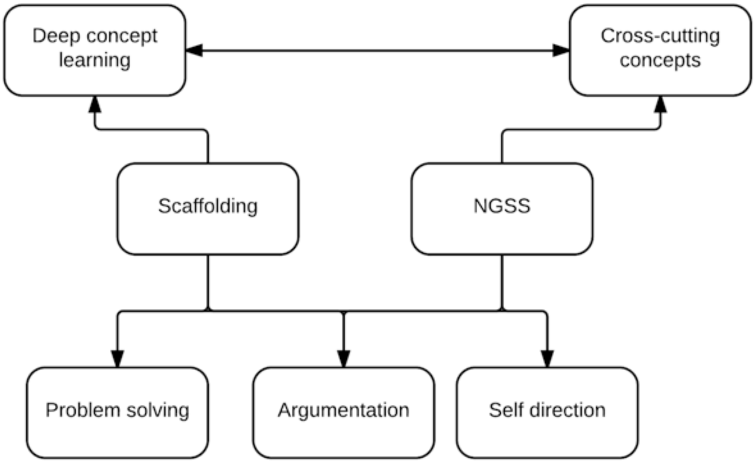

Fig. 4.1 The relationship between the intended learning outcomes of instructional scaffolding and of the Next Generation Science Standards (Achieve, 2013)

The interrelationship between the intended learning outcomes of scaffolding and of the NGSS are illustrated in Fig. 4.1 and expanded upon in the sections that follow.

4.2.1 Higher-Order Thinking Skills

4.2.1.1 Ill-Structured Problem-Solving Ability

Scaffolding to promote problem-solving ability is closest to the original instructional scaffolding definition (Wood, Bruner, & Ross, 1976). Problem-solving ability in this case refers to the ability to solve ill-structured problems—problems with many possible valid solutions and many valid solution paths (Jonassen, 2000, 2011).

To be successful solving ill-structured problems, learners need to qualitatively model such problems so that they can determine what entities interact in the problem, how they interact, and what such interaction means to each entity (Chi, Feltovich, & Glaser, 1981; Jonassen, 2003; Klahr & Simon, 1999; Lesh & Harel, 2003; Nersessian, 2008). But then they need to characterize the disparity between the goal state and the current state and determine an appropriate way to bridge the gap (Jonassen, 2000). However, this process is different from the means-ends analysis that describes how people often solve well-structured problems. Rather, solving ill-structured problems is an iterative process of defining the problem and identifying and weighing potential goal states and different methods of arriving at those goal states (Chi et al., 1981; Giere, 1990; Jonassen, 2000, 2003; Nersessian, 2008). By definition, ill-structured problems often have many solutions that are equally valid (Jonassen, 2011). In this way, the suitability of solutions to ill-structured problems needs to be judged on the basis of evidential support (Belland, Glazewski, & Richardson, 2008; Ford, 2012; Jonassen & Kim, 2010). Students thus need to have the opportunity to build and evaluate evidence-based arguments to be able to engage in ill-structured problem-solving, and to prepare for the modern workforce (Ford, 2012; Gu & Belland, 2015; Jonassen, 2011; Osborne, 2010; Perelman & Olbrechts-Tyteca, 1958).

The ability to solve ill-structured problems is qualitatively different from solving well-structured problems such as the story problems found in many mathematics textbooks (Jonassen, 2000; Lesh & Harel, 2003; Nersessian, 2008). One can solve well-structured problems with only the information given in the problem description, whereas solving ill-structured problems requires the acquisition, evaluation, and use of much data beyond that given in the problem description. Well-structured problems have only one correct answer, and often only one solution path, whereas ill-structured problems have multiple potentially correct solutions, and many ways of arriving at them. Given these differences, the strategies by which one addresses well-structured problems and ill-structured problems differ (Jonassen, 2000). As such, one cannot promote the enhancement of ill-structured problem-solving ability by engaging students in well-structured problem-solving; rather, one should engage students in ill-structured problem-solving along with instructional support such as scaffolding (Abd-El-Khalick et al., 2004; Jonassen, 2011).

4.2.1.2 Argumentation Ability

Argumentation ability refers to the ability to back claims with evidence by way of premises, and evaluate and respond to the extent to which claims presented by others are well supported by evidence (D. Kuhn, 1991; Perelman & Olbrechts-Tyteca, 1958; van Eemeren, Grootendorst, & Snoeck Henkemans, 2002). Two prominent models of argumentation are those of persuasive argumentation and dialectical argumentation. According to the former, there is no such thing as a universally valid argument; rather, arguments are successful to the extent to which the audience agrees with its central claim. As such, the goal of argumentation is to lead the audience to adhere to the validity of one's claim (Perelman & Olbrechts-Tyteca, 1958; Walton, 1989). In persuasive argumentation, novice arguers often focus on strengthening one's own position (D. Kuhn, 1991; Vellom & Anderson, 1999).

Dialectical argumentation starts off with individuals creating evidence-based arguments, but from there it diverges. Specifically, rather than simply supporting one's own claims, in dialectical argumentation, one also engages with claims of others (Asterhan & Schwarz, 2009; Jonassen & Kim, 2010; Keefer, Zeitz, & Resnick, 2000). This can include attempting to weaken the position of others (Asterhan & Schwarz, 2009; D. Kuhn, 1991) or negotiating with opposing parties in pursuit of an ultimate truth (Jonassen & Kim, 2010; Keefer et al., 2000; van Eemeren & Houtlosser, 2001). In the latter case, the opposing parties make concessions in their arguments in the service of improving their claims and ultimately moving toward an ultimate truth that is not directly knowable, but which can be approached through negotiation of arguments.

Argumentation can be considered a subset of problem-solving ability (Jonassen & Kim, 2010; D. Kuhn, 1991), and is the process by which scientific knowledge advances (Ford, 2012; Osborne, 2010). As discussed earlier, argumentation is core to how the quality of solutions to ill-structured problems is judged. Having arrived at initial solutions to such problems, argumentation is also how such solutions are iteratively improved, as well as the evidential support for the solutions (Ford, 2012; Osborne, 2010). K-12 (Belland et al., 2008; Driver, Newton, & Osborne, 2000; Glassner, Weinstock, & Neuman, 2005; McNeill & Pimentel, 2010) and college students (Abi-El-Mona & Abd-El-Khalick, 2011; Cho & Jonassen, 2002; Uskola, Maguregi, & Jiménez-Aleixandre, 2010) often struggle with argumentation, and thus it is important to help them learn this skill. But rather than teaching such didactically, it is important to put them in a situation about which to argue (Aufschnaiter, Erduran, Osborne, & Simon, 2008; Belland et al., 2008; Driver et al., 2000; Jonassen & Kim, 2010) and support them with such tools as scaffolding (Belland et al., 2008; Cho & Jonassen, 2002; Clark & Sampson, 2007; Nussbaum, 2002).

4.2.1.3 Self-Directed Learning Ability

Self-directed learning refers to the ability to identify learning issues, plan and execute a strategy to address the learning issues, and evaluate the quality with which the learning issues were addressed; in other words, it is the ability to identify and regulate one's pursuit of learning issues (Bolhuis, 2003; Loyens, Magda, & Rikers, 2008). Being able to do so is central to addressing ill-structured problems (Giere, 1990; Jonassen, 2011; Nersessian, 2008), and thus is an important skill to support to facilitate student success in problem-centered approaches to instruction (Lohman & Finkelstein, 2000; Loyens et al., 2008; Merriënboer & Sluijsmans, 2008).

Identifying learning issues to be addressed requires that learners assess what information is needed to address the problem, and what among the needed knowledge is a knowledge deficiency—either not present in the problem presentation or part of their preexisting knowledge (Hmelo-Silver, 2004; Loyens et al., 2008). This allows for a good deal of autonomy on the part of students in that they can define the content to be learned, which in turn can enhance student motivation (Deci & Ryan, 2000; Wijnia, Loyens, & Derous, 2011). This clearly goes beyond the traditional practice in teacher-centered classrooms in which the teacher determines what is to be learned.

Planning and executing a strategy to address learning issues requires that learners select appropriate learning resources (Hmelo-Silver, 2004; Loyens et al., 2008). The effective evaluation of the quality of sources is considered key to information literacy and solving problems, as without it, one can be lost in the vast amount of information on the web, and not be able to distinguish between credible information and non-credible information (Berzonsky & Richardson, 2008; Van de Vord, 2010). Yet, college (Berzonsky & Richardson, 2008; Van de Vord, 2010) and K-12 (Kuiper, Volman, & Terwel, 2005; Nicolaidou, Kyza, Terzian, Hadjichambis, & Kafouris, 2011; Williams, 2005) students often experience much difficulty searching for and effectively evaluating the quality of online information. For example, K-12 students often search for information in an unsystematic manner and rapidly decide if a page is usable; they then quickly search for an answer to a specific question (Kuiper et al., 2005). Furthermore, K-12 students often see all evidence as equally valid (Nicolaidou et al., 2011). Unaided college science students are often unable to distinguish between peer-reviewed sources and non-peer-reviewed sources (Berzonsky & Richardson, 2008). Students' poor ability to evaluate and use sources effectively can stem from such phenomena as conflicting information across sources, complexity of the target information and the way in which it is portrayed, and the structure that the text follows (Britt, Richter, & Rouet, 2014). Unsophisticated epistemic beliefs can cause students to struggle to distill important messages from sources and fail to question the credibility of sources (Bråten, Britt, Strømsø, & Rouet, 2011). Furthermore, students' evaluation of sources is often short-circuited by a desire for quick learning (Berzonsky & Richardson, 2008; Zimmerman, 1995), which is often experienced by students with unsophisticated epistemic beliefs (Chinn, Buckland, & Samarapungavan, 2011; Hofer & Pintrich, 1997; Qian & Alvermann, 1995). Clearly, students' struggles identifying appropriate learning issues and determining promising ways to address such present a prime opportunity to use computer-based scaffolding (Kuiper et al., 2005).

The last part of self-directed learning ability is the ability to evaluate the quality of one's own learning and learning processes, also known as metacognition (Loyens et al., 2008; Quintana, Zhang, & Krajcik, 2005; Schraw, Crippen, & Hartley, 2006). Metacognition is desirable in part to enable the smooth operation and success of a student-centered learning environment. This is because if students define and pursue their own learning issues, and different student groups in the same classroom pursue a wide variety of learning issues in a wide variety of manners, it is difficult for one teacher to provide sufficient feedback to ensure that all students are on the right track. Metacognition can work in concert with teacher feedback to provide a consistent corpus of feedback to inform the revision of learning processes as needed. Metacognition has been an important process that scaffolding seeks to support (Cuevas, Fiore, & Oser, 2002; Quintana et al., 2005).

4.2.1.4 Alignment with NGSS

The intended learning outcome of promoting higher-order thinking skills aligns with NGSS's emphasis on students learning STEM processes and engaging with the culture of STEM and with authentic STEM issues (Achieve, 2013; National Science Board, 2010), as detailed in the following sections.

4.2.1.4.1 STEM Processes

The goal of helping students learn to apply STEM processes includes helping students learn to (a) identify important problem characteristics to investigate further, (b) design strategies to investigate those problem aspects, (c) interpret appropriately data and other information collected, (d) arrive at reasonable conclusions, and (e) engage in a variety of valued scientific discourse patterns (Achieve, 2013; Duschl, 2008; National Science Board, 2010). This does not mean that all citizens need to know and be able to apply such processes at the same level as a professional chemist or engineer, but they should be able to converse with STEM processes and issues to the extent that they can make informed decisions about scientific issues that impact their local communities and nation (Duschl, 2008; Kolstø, 2001; Sadler, Barab, & Scott, 2007). Each of these subpoints is addressed in the following pages.

4.2.1.4.1.1 Identify Important Problem Characteristics to Investigate Further

One of the key processes in STEM is asking cogent questions and identifying key aspects of problems (Carr, Bennett, & Strobel, 2012; Giere, 1990; Klahr & Simon, 1999; National Research Council, 2012; Nersessian, 2008). Going into a problem with a vague goal of figuring it out is unlikely to lead to a meaningful solution (Jonassen, 2011). Rather, one needs to determine the involved variables, how they interact, and what about how they interact is problematic (Belland et al., 2008; Jonassen, 2011). This is a key scientific process, and one that does not require the asker to be a professional scientist. But it is a skill that individuals do not naturally have; rather, it needs to be developed through instruction (Jonassen, 2003). By habitually asking questions about scientific phenomena, citizens will identify key issues facing their communities, and be prepared when others present arguments and explanations about STEM-related issues in their community (Kolstø, 2001; Sadler et al., 2007; Zeidler, Sadler, Simmons, & Howes, 2005).

4.2.1.4.1.2 Design Strategies to Investigate Problem Aspects

Students need to think of scientific problems from different perspectives (Jonassen, 2011). They also need to recognize and apply the key role of iteration in addressing scientific questions (Klahr & Simon, 1999; Nersessian, 2008). Specifically, they need to understand that one cannot effectively address a scientific question with just one piece of scientific evidence. Rather, they need to collect data/reason scientifically in one way, consider the limitations of such, and design and carry out additional investigations accordingly (Carr et al., 2012; Giere, 1990; Klahr & Simon, 1999). In other words, they need to understand STEM from an epistemological standpoint—for example, that one cannot arrive at definitive answers to STEM questions by consulting just one source or conducting just one investigation (Chinn et al., 2011; Duschl, 2008; Hogan & Maglienti, 2001; Mason, Boldrin, & Ariasi, 2010; Sandoval, 2005) and that most knowledge is not certain (Bråten et al., 2011; Giere, 1990; Hofer & Pintrich, 1997). But it is not enough to simply understand this; citizens need to also be able to and be willing to apply this understanding to real STEM problems (Chinn et al., 2011; Mason & Scirica, 2006).

In designing investigations, students need to be able to apply the tools of mathematics and computation, and recognize the influence of such tools and specifically the ways in which the tools are used in the problem solution process (Lesh & Harel, 2003; National Research Council, 2012; Schoenfeld, 1985). It is important to note that applying the tools of mathematics does not simply mean setting up equations. Rather, it is important to think, at a conceptual level, about what type of data should be collected and how it will be analyzed to address the research questions (Kerlinger & Lee, 2000; Schoenfeld, 1985). This is important so that the right type of data is collected. At the same time, students need to understand that not all problem-solving strategies need to involve the use of mathematics. Rather, attempting to see where the presented problem and an idealized, qualitative model depart from each other is a viable problem-solving strategy (Nersessian, 2008).

4.2.1.4.1.3 Interpret Data and Other Information Appropriately

Students need to be able to analyze data in a systematic manner, but also realize that the job is not done until such analysis is interpreted in light of a theoretical framework (Giere, 1990; National Research Council, 2012). This is important because many individuals have the mistaken impression that scientific investigations always take place in a theoretical vacuum. To the contrary, theoretical frameworks always drive the design, conduction of, and interpretation of the results of research (Abi-El-Mona & Abd-El-Khalick, 2011; Ford, 2012; Giere, 1990; D. Kuhn, 2010). For example, theoretical frameworks can influence the choice of problems to investigate and the selection of variables on which to focus in an investigation (Lather, 2012; Miles & Huberman, 1984). Furthermore, knowing that differences in property A are statistically different between two objects means little without interpreting the finding in light of a theoretical framework. This is important both as something to do when investigating scientific phenomena, but also to remember that other scientists themselves do this when investigating scientific phenomena (Abi-El-Mona & Abd-El-Khalick, 2011; Giere, 1990).

4.2.1.4.1.4 Arrive at Reasonable Conclusions

Much of arriving at reasonable conclusions involves interpreting findings in light of a theoretical framework (Abi-El-Mona & Abd-El-Khalick, 2011). But it also involves actively searching for conflicting findings in the literature. For K-12 students, the literature includes books, interviews with experts, and Internet resources. K-12 students need to be able to reconcile conflicting findings to arrive at reasonable conclusions. This can involve looking for what the preponderance of studies show, privileging findings from more reputable sources, considering limitations and delimitations of studies, and synthesizing different elements of findings to create a cohesive whole (Britt et al., 2014). This is a challenging activity for such students (Bråten et al., 2011), who often are blinded by my-side bias (Britt et al., 2014; D. Kuhn, 1991; Stanovich & West, 2008).

4.2.1.4.1.5 Engage in Scientific Discourse Patterns

Students also need to know and be able to apply and interpret patterns of STEM discourse, including explanations (Britt et al., 2014; Sandoval, 2003) and persuasive and dialectical argumentation (Bricker & Bell, 2008; Ford, 2012; Osborne, 2010; Perelman & Olbrechts-Tyteca, 1958). Behind all scientific explanations are theories, data, and/or biases. Students need to be able to recognize such, both as they create scientific explanations, but also as they interpret those produced by others. For example, if a proposal is advanced to dam a river to produce power, citizens need to be able to weigh the proposed benefits and drawbacks. Furthermore, they need to be able to judge the extent to which an arguer's stakeholder position influences his/her biases, and by consequence, his/her claims and evidence advanced in support of his/her position. As part of this process, they need to be able to evaluate the credibility of evidence, something with which K-12 and college students often struggle (Britt et al., 2014; Nicolaidou et al., 2011).

4.2.1.4.2 Engaging in the Culture of STEM

Key to helping students engage in the culture of STEM is helping them learn the iterative nature of STEM, as well as the importance of modeling, argumentation, and epistemology.

4.2.1.4.2.1 Iterative Nature of STEM

Engaging students in the culture of STEM does not mean getting students to engage in the "scientific method," as the latter is in fact heavily simplified (Abd-El-Khalick, 2012; Lawson, 2010; Tang, Coffey, Elby, & Levin, 2010). STEM professionals do not always start an investigation with a hypothesis, but often engage in an exploratory investigation to identify pertinent variables or to simply observe and describe a system (Franklin, 2005; Klahr & Simon, 1999; Lawson, 2010). For example, exploratory investigations helped scientists uncover the phenomenon of gene expression (Franklin, 2005). Such exploratory studies often do not involve a control condition, and yet they can lead to very important scientific discoveries, and guide further inquiry (Klahr & Simon, 1999). That is, they can indicate and lead to descriptions of important phenomena. As such observations accumulate, STEM professionals can begin to build theory to explain the phenomena. Further investigations can explore whether the new theory explains and predicts other instances of similar phenomena (Klahr & Simon, 1999; Lawson, 2010).

This accumulation of studies along a line of inquiry does not proceed in a linear manner. Rather, it proceeds in fits and starts—in a very iterative manner. Students should have the opportunity to experience the iterative nature of STEM (T. S. Kuhn, 1996; Lammi & Becker, 2013; Nersessian, 2008). The iterative nature holds at its core theory; theory drives the creation of problem representations (modeling; described below), the design and conduct of investigations to understand problems further, the creation of claims, and backing claims with evidence (argumentation; described below) (Giere, 1990; Klahr & Simon, 1999; Nersessian, 2008). The initial model of a problem situation will necessarily be idealized; it can be improved through such processes as establishing limiting cases (Nersessian, 2008), reacting to phenomena that cannot be sufficiently explained through existing theory (Klahr & Simon, 1999) and engaging with other STEM professionals who often apply different perspectives to problems (Giere, 1990). Not all citizens will engage in the entire process of model-building, but they need to understand the process such that they can engage in authentic scientific discourses centered on locally relevant scientific problems (Kolstø, 2001; Sadler et al., 2007).

Scientists need to revisit theory at multiple stages within the problem-solving process, as it can provide a lens through which to view and interpret data, and suggest new directions to go in an investigation (Giere, 1990; Nersessian, 2008). For example, the discovery of the double helix structure of DNA did not occur all at once, but rather happened through iteration of ideas and interaction with arguments from other scientists (Crick, 1974). Needing to iterate toward an ever-improving solution to a scientific problem can be frustrating to students (Belland, Kim, & Hannafin, 2013). Furthermore, students can often see authentic science as consisting of only collecting data, and not analyzing such (Gu, Belland, Weiss, Kim, & Piland, 2015). Thus, it is important to help students control negative emotions and promote positive emotions throughout this process (Belland et al., 2013; Kim & Hodges, 2012; Kim & Pekrun, 2014; Turner & Husman, 2008). But it is also important to help students perceive that they can be successful in this endeavor (Bandura, 1977; Belland et al., 2013; Britner & Pajares, 2006) and that it is of value (Belland et al., 2013; Wigfield & Eccles, 2000).

4.2.1.4.2.2 Modeling

To be conversant in STEM, individuals also need to be able to use the tools of science, engineering, and mathematics to model natural phenomena, and use those models in reasoning and argumentation (Anzai & Yokoyama, 1984; Lesh & Harel, 2003; Pluta, Chinn, & Duncan, 2011; Sensevy, Tiberghien, Santini, Laubé, & Griggs, 2008; Stratford, Krajcik, & Soloway, 1998). This means representing the constituent parts of the system and how they interact. This is key to the first part of problem-solving—representing the problem (Chi et al., 1981; Jonassen, 2003). It is important to be able to model phenomena both qualitatively and also with the language of mathematics (Chi et al., 1981; Giere, 1990; Jonassen, 2011; Larkin, McDermott, Simon, & Simon, 1980). Modeling phenomena qualitatively means thinking widely about the involved entities, using words rather than numbers to describe how such entities interact and connecting the problem elements to existing domain knowledge (Anzai & Yokoyama, 1984; Jonassen, 2003; Lesh & Harel, 2003). However, students often suffer from limited understanding of complex causality, which can limit their ability to model a problem appropriately (Hmelo-Silver & Pfeffer, 2004; Perkins & Grotzer, 2005). That is, one cannot identify a factor A that directly causes factor B in all systems; students who think that they should always find such a relationship will likely often create an incorrect model (Perkins & Grotzer, 2005).

Students often also suffer from a poor understanding of the words with which to precisely describe a scientific relationship; this can lead them to construct representations of scientific phenomena that do not reflect reality (Leont'ev, 1974; Sensevy et al., 2008). Furthermore, they often perceive that they need to enter values from the problem description into an equation, rather than attempt to construct a qualitative representation (Van Heuvelen & Zou, 2001). When developing a qualitative model, a representation is conducted at first in a learner's mind, and then can be externalized in such forms as a concept map, a textual representation, and/or a diagram (Chi et al., 1981; Jonassen, 2003). The process of articulation can lead to improvement of the model (Belland et al., 2008; Land & Zembal-Saul, 2003; Quintana et al., 2004). Qualitative representations can then be iteratively improved.

Modeling phenomena with mathematics includes setting up an equation that describes the phenomena. It is important to note that effective problem solvers do not solely model problems qualitatively or quantitatively; rather, they use both sorts of representation, as each informs the other and together can lead to a more effective solution and solution process (Chi et al., 1981; Jonassen, 2003; Van Heuvelen & Zou, 2001). For example, after creating a qualitative model, one may proceed to create a quantitative model. The finished qualitative model will influence how the quantitative model is set up. One should then see where the models are consistent, and where they contradict each other; in this way, the models can be progressively improved. By spending adequate time modeling, one can engage in more effective problem-solving, as it guides subsequent investigations, can activate solution schemas, and can provide the framework by which one can simulate what would happen when a variable is manipulated (Anzai & Yokoyama, 1984; Chi et al., 1981; Jonassen, 2003; Sins, Savelsbergh, & van Joolingen, 2005).

Just as it is important to learn to create models, it is also important to be able to interpret the models created by others, especially in terms of what these diverse models say differently about the underlying problems (diSessa, 1988; Seufert, 2003; Wu, Krajcik, & Soloway, 2001). Doing so can lead to enhanced understanding of the problem (Seufert, 2003). This is particularly challenging for K-12 students (Bråten et al., 2011; Seufert, 2003). Indeed, learners often simply adhere to the model that is closest to their own early experiences, or the simplest explanation of the underlying phenomenon, even when presented with a more accurate model (diSessa, 1988; Perkins & Grotzer, 2005). This may be explained in part by most K-12 students' lack of familiarity with complex causal models, such as those that explain changes in a factor through indirect action from a combination of factors A and B (Perkins & Grotzer, 2005). While some evidence indicates that reluctance to consider an alternative model is widespread among learners of differing levels of prior knowledge and skill, other evidence indicates that it may be more prevalent among lower-achieving students (Seufert, 2003). Thus, it is especially important to endeavor to increase modeling skills from a social justice vantage point and to broaden participation in STEM (Lynch, 2001).

4.2.1.4.2.3 Argumentation

Science is very much a social endeavor, as no scientist works in a vacuum (Ford, 2012). Rather, scientists work in a large community of practice in which they share and defend findings to one another, and build off of others' work. At the core of this is argumentation, defined as both backing claims with evidence and models, but also effectively evaluating claims on the basis of evidence and models (Ford, 2012; Osborne, 2010). The argumentation process allows scientific models and theories to be iteratively improved (Ford, 2012). To be able to engage in STEM effectively as citizens, individuals also need to be able to engage in clear argumentation (Aufschnaiter et al., 2008; Jonassen, 2011; Osborne, 2010; Perelman & Olbrechts-Tyteca, 1958). For example, when scientific issues are discussed, citizens need to be able to sort out well-founded claims from less-well-founded claims. K-12 students (Hogan & Maglienti, 2001; Weinstock, Neuman, & Tabak, 2004) and adults (D. Kuhn, 1991) often struggle to evaluate arguments, in part due to poor ability to evaluate the credibility of evidence (Bråten et al., 2011; Nicolaidou et al., 2011).

There are several key areas that need to be addressed in the course of learning to argue. First, there is the conceptual level—helping students understand what a well-founded argument is and is not, and by extension recognize strong and weak arguments. After all, before one can hope to help students learn a skill, they need to be familiar at a conceptual level with the skill that is being learned (Wood et al., 1976). Specifically, students need to understand that an argument is linking a claim to evidence by way of premises to which the claimer and the audience adhere, in the pursuit of leading the audience to adhere to the claim (Perelman & Olbrechts-Tyteca, 1958). A well-founded argument is one that performs this function well, within the framework of generally accepted rhetorical principles. Being able to distinguish between strong and weak arguments relies in part on sophisticated epistemological understanding (Hogan & Maglienti, 2001; Weinstock et al., 2004), which refers to how one thinks that knowledge is established and justified (Mason & Scirica, 2006). This is described in more detail in the next section.

Next, individuals need to learn about the process of argumentation. This involves first making a claim. But before one can establish a claim, one needs to thoroughly understand the underlying problem, including the involved entities and how they interrelate. To do so, one needs to define the problem, determine needed information, and find and organize the information (Belland et al., 2008). Next, one needs to connect evidence to the claim. In so doing, one needs to appeal to premises by which the evidence connects to the claims. Ideally, one employs premises with which the audience already agrees (Perelman & Olbrechts-Tyteca, 1958). Premises that are widely held by the majority of the audience can be left unsaid, while premises that are not held as given by the majority of the audience need to be stated (Perelman & Olbrechts-Tyteca, 1958). For example, if one wanted to claim that Brazilians are unhappy that the Brazilian team was knocked out of the World Cup, one could provide evidence that the Brazilian team in fact was knocked out of the World Cup and that many Brazilians are unhappy. One would also rely on a premise that people tend to be unhappy when their national team in their most popular sport loses.

4.2.1.4.2.4 Epistemology

Closely connected to learning argumentation is a need to develop sophisticated epistemic beliefs, defined as beliefs about the sources, certainty, justification, and simplicity of knowledge that align with that of most STEM professionals (Bendixen & Rule, 2004; Hofer & Pintrich, 1997). With sophisticated epistemic beliefs, an individual knows that claims need to be supported with well-justified, converging evidence, such as evidence collected through tests of a refutable question (Chinn et al., 2011; Hogan & Maglienti, 2001; Mason & Scirica, 2006; Weinstock et al., 2004). Next, with sophisticated epistemic beliefs, one understands that justification for knowledge claims should come from rational arguments or empirical evidence, rather than an appeal to authority (Hogan & Maglienti, 2001;

Jiménez-Aleixandre, 2014). Furthermore, with sophisticated epistemic beliefs, one understands that arriving at correct information/conclusions will often not happen instantaneously (Chinn et al., 2011; Greene, Azevedo, & Torney-Purta, 2008). Someone with sophisticated epistemic beliefs will also understand that most knowledge is not certain, and rather is subject to verification through further research (Hofer & Pintrich, 1997). Without sophisticated epistemic beliefs, individuals often jump to erroneous conclusions (Hofer, 2001; Weinstock et al., 2004). Epistemic beliefs influence individuals' ability to interpret conflicting information from multiple scientific texts (Bråten et al., 2011). The sophistication of middle school students' epistemic beliefs significantly predicted their ability to produce arguments, counter-arguments, and rebuttals (Mason & Scirica, 2006). Epistemic beliefs have also been associated with conceptual change: the more sophisticated the epistemic beliefs, the easier it is to achieve conceptual change given the proper instruction, and vice versa (Hofer, 2001).

4.2.1.4.3 Engaging with Authentic STEM Issues

To be clear, the idea of helping all citizens learn some cross-cutting concepts does not mean reestablishing a rhetoric of conclusions approach to science education (Chinn & Malhotra, 2002; Duschl, 2008)—one focused on transmitting an unchanging body of scientific knowledge. Rather, it means to teach core concepts in science for which evidence is overwhelming, such as the role of DNA and genetic expression in determining such characteristics as the size, shape, and function of organisms. One can do this by engaging students with authentic STEM problems. *Authentic problems* are characterized by the following factors: they (a) are locally relevant, (b) have multiple valid solutions and solution paths, and (c) relate to one or more aspects of STEM, and addressing them requires the use of the tools of the discipline (Barab, Squire, & Dueber, 2000; Chinn & Malhotra, 2002; Hung & Chen, 2007; Jonassen, 2011).

Authentic problems suitable for use in STEM education include (a) dilemmas, a problem type represented by many socioscientific issues, and (b) design problems, which may be centered in or at least involve engineering education (Jonassen, 2000). A socioscientific dilemma can address whether a factory should be built that would cause pollution and degrade habitat, but would increase jobs (Tal & Kedmi, 2006). To address this problem, students need to consider such scientific concepts as what contributes to the health or lack thereof of coastal habitats. But they also need to consider social equity issues related to the right to work in an appropriate job. Many such problems can involve multiple areas within STEM, as interdisciplinary work can lead to more robust problem solutions (Belland & Fee, 2012; Porter & Rafols, 2009) and is becoming more common in STEM research (Murray, Atkinson, Gilbert, & Kruchten, 2014; Porter & Rafols, 2009).

A design problem could involve how to use design to prevent erosion while supporting local habitat on barrier islands (Kolodner et al., 2003). To address this problem, middle school students need to employ engineering design principles and processes, draw on scientific knowledge, identify and research needed knowledge, and engage in extensive iteration. This engages students in the culture of STEM, but also helps them gain important STEM skills and knowledge. Another design problem could involve the design of an alarm to respond to specific needs (Silk, Schunn, & Cary, 2009). Addressing this problem again requires the use of engineering approaches and scientific knowledge.

Requiring the use of the tools of the discipline means that students should need to engage in similar processes and use similar tools as professionals in the target field (Chinn & Malhotra, 2002; Hung & Chen, 2007). It is clear that no students except the most advanced graduate students will use exactly the same processes and tools as professional scientists and engineers, but they should use similar epistemic processes, defined as approaches to designing and conducting investigations, as well as interpreting data and making conclusions (Chinn & Malhotra, 2002).

4.2.2 Learning Content Deeply

Learning content deeply goes beyond simple declarative learning; rather, it refers to the ability to describe knowledge in one's own words and apply it to new situations, as well as recognize the connections between the knowledge and related knowledge (Belland et al., 2009; Bloom, Englehart, Furst, Hill, & Krathwohl, 1956). This outcome has been the focus on much work in scaffolding. One line of such research is that of knowledge integration (Clark & Linn, 2013; Linn, 2000). According to this framework, the knowledge learners bring to school does not need to be replaced by more accurate models, but rather can be used as a base on which to build greater understanding. This is because students' existing knowledge base about science consists of mini theories developed through experience that may be at least partially correct (diSessa, 1988). One can help students build upon their existing knowledge base by encouraging them to engage in authentic problem-solving scenarios supported by scaffolds. However, the goal is not directly to improve problem-solving ability. Rather, it is to help students (a) build enhanced mental models of such things as natural phenomena, and (b) realize that what they are learning applies equally well at home and out in the world as in school (Clark & Linn, 2013; Linn, 2000). However, there is the thought that this in turn could lead to more effective problem-solving (Linn, 2000).

Another line of research on scaffolding that focuses on deep content learning is that of intelligent tutoring systems. In this context, learning content deeply has a different meaning than in scaffolding to support knowledge integration. Namely, intelligent tutoring systems seek to develop students' procedural (production rules) and declarative knowledge related to a particular skill (Anderson, Matessa, & Lebiere, 1997; Self, 1998; VanLehn, 2011). Scaffolding embedded in intelligent tutoring systems helps students apply declarative knowledge to problems. In this way, students develop production rules by which the declarative knowledge can be applied without conscious control to similar problems in the future (Koedinger & Aleven, 2007). But Adaptive Character of Thought-Rational (ACT-R) also endeavors to help students learn declarative knowledge deeply, which means that it can be deployed independently in the future.

4.2.2.1 Alignment with STEM Education Goals

The NGSS and Common Core posit learning content deeply as an important goal (Achieve, 2013; McLaughlin & Overturf, 2012; National Science Board, 2010). For example, one part of the NGSS calls for students to learn cross-cutting concepts. Cross-cutting concepts takes at its core the idea that certain concepts—"patterns; cause and effect: mechanism and explanation; scale, proportion, and quantity; systems and system models; energy and matter; flows, cycles, and conservation; structure and function; and stability and change"—are applicable across a range of STEM disciplines (National Research Council, 2012, p. 3). For example, cause and effect applies equally in science and engineering, and indeed among the many subdisciplines in science and engineering. It is important to note that one cannot always find a single cause that by itself leads to a given effect; often there are multiple causal factors that either together lead to the given effect, or which moderate each other's effect (Hmelo-Silver, Marathe, & Liu, 2007; Perkins & Grotzer, 2005). Seeking to find causal factors for phenomena is a core activity in science (Achieve, 2013) and engineering (Brophy, Klein, Portsmore, & Rogers, 2008; Carr et al., 2012). Furthermore, in engineering, one most often aims to design a product, tool, or strategy that causes a desired outcome (National Research Council, 2012). Considering scale, quantity and proportion is just as important in physics as it is in chemistry, and indeed is important in mechanical and other forms of engineering.

Such cross-cutting concepts are key to the participation of common citizens in discourses about STEM problems. For example, without knowing about flows and cycles as well as systems, one would not be able to intelligently discuss issues related to water quality and access. It is unreasonable to expect everyone to take environmental science classes to learn about such concepts within the context of water quality, and chemistry classes to learn about the application of such concepts in chemistry, and so on. Rather, the hope is that students can learn the concept as a cross-cutting concept in one context, and add depth to their knowledge when learning the same cross-cutting concept in another context, as in a spiral curriculum (Achieve, 2013; Bruner, 2009). Or, at the very least, they would have the base knowledge so that when an authentic socioscientific issue arises, they would be able to converse with it intelligently (Reiser, Krajcik, Gouvea, & Pellegrino, 2014).

Cross-cutting concepts may be best learned in the context of problem-centered instructional models (National Research Council, 2007, 2012). However, abstracting a generalizable cross-cutting concept from such a problem is not easy (Perkins & Grotzer, 2005). First, the target concept may be experienced as context-specific by the student (Perkins & Salomon, 1989). Next, it is not an easy feat to both encode such a concept and include the necessary information to be able to retrieve it later in a new situation in which the concept could be applied (Perkins & Grotzer, 2005). Thus, one may need to be explicit about the cross-cutting nature of concepts, as well as situations in which they can be applied in the future, though this does not need to be done in a didactic manner.

The NGSS also call for students to learn disciplinary core ideas, defined as a few key ideas in each STEM discipline around which one can build STEM curricula (Achieve, 2013; National Research Council, 2012). For example, a core idea in physical sciences revolves around the structure and properties of matter (National Research Council, 2012). A core idea in life sciences relates to the growth and development of organisms (National Research Council, 2012). This approach reflects in many ways the idea of science from a few ideas—the idea that it is more important to know very well a few core ideas in a scientific field, rather than know less well a wide breadth of topics in the given science discipline (Clark, 2000; Pritchard, Barrantes, & Belland, 2009; Schmidt, Wang, & McKnight, 2005). The six countries that performed the best in the Third International Mathematics and Science Study (TIMSS) focused on a much narrower range of key science concepts than most states/districts in the USA (Schmidt et al., 2005). Understanding core ideas does not mean simply being able to describe the idea, but rather to use the idea to describe natural phenomena (Bloom et al., 1956; Reiser et al., 2014). This aligns with the focus on deep content learning of much scaffolding (Clark & Linn, 2013; Linn, Clark, & Slotta, 2003).

4.2.3 Results from Meta-Analysis

In the meta-analysis, outcomes were coded according to whether scaffolding in the studies aimed to increase higher-order thinking skills ($n_{outcomes}=237$), content learning ($n_{outcomes}=95$), or motivation ($n_{outcomes}=1$; See Table 4.1; Belland et al., In Press). This means that 71.2% of included outcomes aimed at enhancing higher-order skills, 28.5% aimed at enhancing content knowledge, and 0.3% aimed to enhance motivation. Results indicated that there was no statistically significant difference between average effect sizes when scaffolding intended to increase higher-order thinking skills ($g=0.45$) versus deep content learning ($g=0.50$). This suggests that scaffolding is a robust instructional approach that can be used to promote diverse learning goals. This is interesting, in that educational interventions tend to not have equally positive influences on content learning and higher-order skills. For example, lecture is well known to be efficient and effective at influencing content learning, but to be ineffective at influencing higher-order thinking abilities (Albanese & Mitchell, 1993; Bland, Saunders, & Frisch, 2007). Problem-based learning tends to lead to strong impacts on higher-order thinking skills, and not on immediate recall of content (Gijbels, Dochy, Van den Bossche, & Segers, 2005; Walker & Leary, 2009). Thus, scaffolding appears to remedy one of the weaknesses of problem-based learning, by helping students learn content knowledge effectively.

Table 4.1 Table of results of moderator analyses on the effect of intended learning outcome on cognitive outcomes

Level	*n* outcomes	Effect size estimate	95% confidence interval	
			Lower limit	Upper limit
Content learning	95	0.50	0.41	0.58
Enhance motivation	1	0.86	0.2	1.52
Higher-order thinking	237	0.45	0.39	0.51

4.3 Assessment

Scaffold designers can set out to design scaffolds with the intention of enhancing students' higher-order thinking abilities or content knowledge. But to be able to verify if the scaffolding that is produced actually enhances such knowledge and skills, it is necessary to consider how the learning is assessed (Cronbach, 1949; Messick, 1989). After all, an assessment that is on the topic of problem-solving does not necessarily assess problem-solving ability. To assess problem-solving, one would need to assess students' abilities to define the problem, determine needed information, and find and synthesize the needed information to arrive at a solution (Belland et al., 2009; Sugrue, 1995).

To assess learning appropriately, it is important to consider the constructs of interest, defined as a characteristic of an individual or group (e.g., intelligence, fluency, and argumentation ability) that cannot be directly measured, and for which one can only measure certain related behaviors (e.g., ability to construct an argument given a scenario and argument construction parameters) (Belland et al., 2009; Kerlinger & Lee, 2000; Messick, 1989). It is necessary to carefully define the constructs to be assessed, and craft a set of activities that can reliably and validly assess the extent to which the test takers evidence a grasp of the target construct (Anastasi & Urbina, 1997; Belland, 2012; Belland et al., 2009; Cronbach, 1949; Messick, 1989). To be reliable, test scores need to be consistent when taken multiple times in close temporal proximity by the same person and also display similar response patterns among people of similar abilities (Kerlinger & Lee, 2000; Messick, 1989). To be valid, a variety of evidence needs to support the conclusion that the set of test scores issuing from the administration of a test are a fair reflection of the amount of the underlying construct the test taker has (Kerlinger & Lee, 2000; Messick, 1989). To be valid, a set of test scores needs to also be reliable (Messick, 1989).

When examining assessment of learning results from the use of computer-based scaffolding, it is useful to consider the assessment framework of Sugrue (1995), who classified assessments in terms of whether they measure at the concept, principles, or application level (see Fig. 4.2). When doing so, it is important to avoid the temptation to label all multiple choice assessments as concept-level assessments, and all open-response assessments as principles or application-level assessments (Hancock, 1994). Measuring at the concept level means that the assessment measures how well students can define or recognize examples of a given concept. This could include assessments ranging from multiple choice tests in which students need to choose a definition, to sorting tasks, and short answer assessments. Measuring at the principles level means that students are provided scenarios involving relationships among several variables and need to predict what would happen if one of the variables were manipulated in a particular way. This again could take many different forms, ranging from multiple choice to writing essays. Measuring at the application level means that students need to design and conduct an investigation using the newly learned material. This is often a performance-based assessment, but can take other forms, such as multiple choice (Hancock, 1994). In many ways, the concept, principles, and application levels parallel the intended learning outcomes

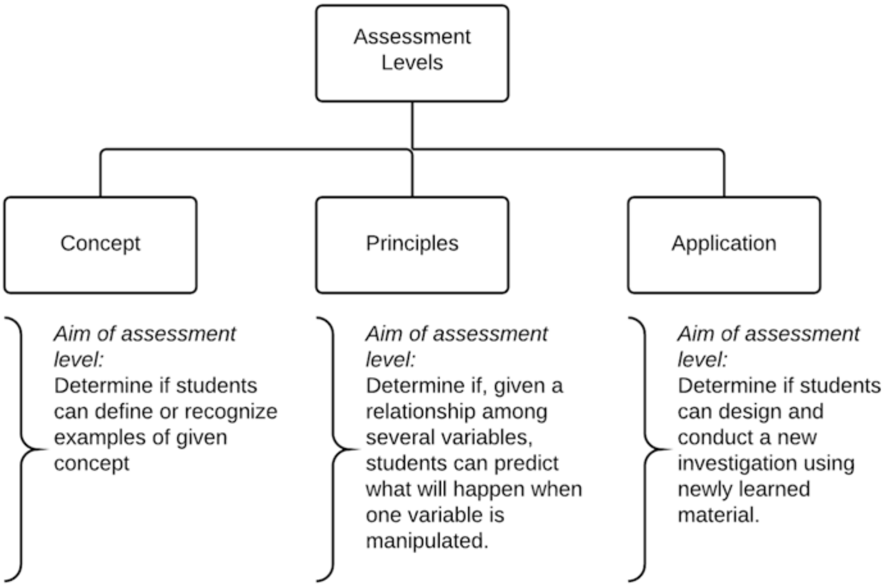

Fig. 4.2 Aims of assessments at the concept, principles, and application levels, as proposed by Sugrue (1995)

of scaffolding. But it is important to make the distinction between intended learning outcomes and assessment levels, as the former are goals towards which designers work when designing scaffolds, and the latter are the ways in which student learning is assessed. These are not always one and the same (Boud & Falchikov, 2006).

4.3.1 Results from Meta-Analysis

It is natural to question whether there are any differences in effect sizes of computer-based scaffolding according to the different assessment levels. For example, if scaffolding is designed to promote problem-solving ability, one would imagine that assessment at the principles or application levels would be more sensitive to the effect of said scaffolding. And if scaffolding is intended to influence content learning, then one would expect that concept-level assessment would be most sensitive to the effect of the scaffolding. Outcomes at the concept level ($n_{outcomes}=125$), principles level ($n_{outcomes}=167$), and application level ($n_{outcomes}=41$) were included (See Table 4.2; Belland, Walker, Kim and Lefler, In Press). Scaffolding's impact on cognitive outcomes was statistically greater when measured at the principles level ($g=0.51$) than when measured at the concept level ($g=0.40$). The effect size for scaffolding at the application level was $g=0.44$. Thus, the effect size point estimate for scaffolding ranged from 0.40 to 0.51 for the three assessment levels. The

Table 4.2 Table of results of moderator analyses on the effect of assessment level on cognitive outcomes

Level	*n* outcomes	Effect size estimate	95 % confidence interval	
			Lower limit	Upper limit
Concept	125	0.40	0.33	0.47
Principles	167	0.51	0.44	0.59
Application	41	0.44	0.32	0.57

95 % confidence intervals—(0.33–0.47), (0.44–0.59), and (0.32–0.57) for concept, principles, and application level assessment, respectively—indicate that one can have great confidence that scaffolding leads to substantial effects across all three assessment levels. This is intriguing, in that it is rare for educational interventions to have such a consistent effect across assessment levels. For example, the underlying instructional models with which scaffolding is used often produce strong effects in one or two of the assessment levels, but not all three. Problem-based learning (PBL) meta-analyses have indicated the PBL leads to effects that are statistically greater than zero at the principles (Gijbels et al., 2005) or the principles and application levels (Walker & Leary, 2009), but not at the remainder of the assessment levels.

There are several possible explanations of the robust effect of scaffolding across assessment levels. First, scaffolding designed to impact higher-order thinking abilities may only be assessed at the principles and application levels, and be mostly successful at influencing student learning as measured by the given assessments; likewise, scaffolding designed to influence content learning may be assessed largely at the concept level, and be mostly successful in influencing learning at that level. Next, it may be possible that scaffolding designed to enhance content learning is also assessed at the principles and application levels, and it also has a positive influence at those levels. It is possible also that scaffolding designed to enhance higher-order thinking abilities is assessed at the concept, principles, and application levels, and leads to strong learning outcomes at all three levels. After all, one of the arguments for promoting content learning in the context of problem-solving is that this will increase students' abilities to solve problems through the enhancement of students' mental models (Anderson, 1983; Clark & Linn, 2013; Johnson-Laird, 2001).

It is especially interesting that scaffolding leads to such a strong effect at the application level. The lower limit of its confidence interval was 0.32, which is an effect of a substantial magnitude—one that is higher than one often finds in educational technology applications for mathematics learning (*ES*=0.15; Cheung & Slavin, 2013). To perform well on an application level assessment, one must understand the target strategy to a sufficient extent to be able to apply it to a new situation (Sugrue, 1995). This is a very difficult bar to clear, as it requires abstraction of the underlying strategy, and application of said strategy in a new situation that likely differs in key aspects. In short, it is essentially far transfer that is being targeted, which is very difficult to promote (Barnett & Ceci, 2002; Salomon & Perkins, 1989).

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Chapter 5
Computer-Based Scaffolding Strategy

Abstract This chapter covers variations in scaffolding strategies along the following characteristics—scaffolding function (e.g., strategic and conceptual), context specificity (i.e., generic or context-specific), customization (e.g., fading and fading/adding), and customization schedule (e.g., self-selected and performance-based). These variations and the theoretical basis for these are explained. Then, results from the meta-analysis are shared, which indicate that there are no differences in cognitive outcomes according to scaffolding function, context specificity, and customization. These results are then discussed.

Keywords Adding · Conceptual scaffolding · Context-specific · Fading · Fading/adding · Fixed customization · Generic · Metacognitive scaffolding · Modeling · Motivation scaffolding · Performance-based customization · Question prompts · Strategic scaffolding · Scaffolding customization · Self-selected customization

5.1 Rationale for Chapter

There is a very large literature on what computer-based scaffolding should do and why, including conceptual frameworks (e.g., Belland, Kim, & Hannafin, 2013; Quintana et al., 2004) and guidelines derived from empirical studies (e.g., Lee & Songer, 2003). While these articles and other reports are often well referenced, by necessity, they only draw on some of the empirical studies/evidence on computer-based scaffolding as well as theoretical analysis. Furthermore, their messages about what forms of scaffolding are most effective are often conflicting. As such, it is difficult for scaffolding designers and researchers to know what scaffolding approaches are most effective under what circumstances.

A key goal of the meta-analysis that I completed with my colleagues was to synthesize empirical evidence on scaffolding so as to uncover the most effective scaffolding strategies in science, technology, engineering, and mathematics (STEM)

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education. This way, scaffolding designers and researchers could have solid, empirically based rationales for using one strategy over another in a particular context. And in the case that variation of a scaffolding characteristic did not influence cognitive outcomes, designers could be relatively confident that their choice would not adversely affect student learning one way or the other[1].

To accomplish this, it was first important to think about ways in which scaffolding strategies can vary. The first such way is the scaffolding function, defined as the focus of its support (Hannafin, Land, & Oliver, 1999). This is different from scaffolding's intended outcome in that scaffolding function focuses on the areas in which scaffolding needs to assist students so as to facilitate student success at the target task. Scaffolding function can be categorized into conceptual scaffolding, strategic scaffolding, metacognitive scaffolding, and motivation scaffolding (Belland, Kim, et al., 2013; Hannafin et al., 1999), each of which is described in the sections that follow, along with meta-analysis results on the relative influence of each type of scaffolding on cognitive outcomes.

Next, one can consider scaffolding in terms of whether it contains embedded content knowledge (context-specific) or not (generic) (Belland, Gu, Armbrust, & Cook, 2013; Davis, 2003; McNeill & Krajcik, 2009). This has to do with whether context-specific information is embedded in the scaffolding support. For example, consider a scaffold that helps students consider where to build a power plant. A generic version of the scaffold may provide a generic process by which individuals can (a) identify needed characteristics of a site for an industrial building, (b) identify locations that have at least some of those characteristics, (c) list pros and cons of the different identified sites, and (d) select a site and build a rationale for why the site is appropriate. A context-specific version may be tailored entirely to the choice of a location for a power plant, and all prompts would be couched in that context. Furthermore, a context-specific scaffold may include the options from which students can choose as well as the information with which students will make their decision. Decisions to embed such information are often based on theories of whether target skills are context-specific or generic (Davis, 2003), a question on which there is much disagreement (Perkins & Salomon, 1989). In the following sections, this scaffolding characteristic is explained, along with the influence of each level of this variable on scaffolding's influence on cognitive outcomes.

Finally, one can consider scaffolding in terms of how it is (or is not) customized. Customization can include fading, adding, fading/adding, or none, and can be done on the basis of performance, self-selection, a fixed schedule, or none (Collins, Brown, & Newman, 1989; Koedinger & Corbett, 2006; Pea, 2004).

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[1] Note: One needs to consider results of meta-analyses alongside results of other research, especially qualitative and other research that would be excluded from meta-analyses. Also, it is important to note that the current meta-analysis only included cognitive outcomes. Other outcomes such as motivational ones are also important in a holistic assessment of the influence of an instructional approach.

5.2 Scaffolding Function

Scaffolding functions include conceptual scaffolding, strategic scaffolding, metacognitive scaffolding, and motivation scaffolding (Belland, Kim, et al., 2013; Hannafin et al., 1999). These are detailed in the following sections, and results from the meta-analysis comparing the effectiveness of such functions are presented.

5.2.1 Conceptual Scaffolding

Conceptual scaffolding guides students in terms of things to consider when solving problems (Hannafin et al., 1999; Sandoval & Reiser, 2004). In any problem, there are a multitude of possible things to consider when solving it, and thus it is important to help students narrow these down and choose more productive considerations (Jonassen, 2000) and make sense of the data and information encountered (Ford, 2012; Quintana et al., 2004). Such scaffolding can take a more structured approach when informed by ACT-R (Anderson, Matessa, & Lebiere, 1997) or knowledge integration (Linn, Clark, & Slotta, 2003), or a less structured approach when informed by activity theory (Belland & Drake, 2013; Luria, 1976). In computer-based scaffolding, conceptual scaffolding can take the form of expert modeling in which an expert discusses what aspects of a problem he/she would consider in the process of addressing a problem (D. D. Li & Lim, 2008; Pedersen & Liu, 2002). For example, in *Alien Rescue*, an expert discussed what considerations he would make when considering what planet to choose as a new home for a stranded alien (Pedersen & Liu, 2002). This led experimental students to develop significantly stronger rationales for their problem solutions and to be less likely to ask vague questions than control students (Pedersen & Liu, 2002). Expert modeling would likely be seen more often in scaffolding informed by activity theory than in scaffolding informed by ACT-R or knowledge integration.

Conceptual scaffolds can also invite students to plan animations or experiments, directing them to areas of planning that are particularly important and to which students should pay great attention, and simplifying areas that are not central to learning goals (Reiser, 2004). For example, a scaffold invited students to plan a chemical reaction animation they would create, create the animation in a modeling tool, explain the meaning of the animation and relate it to the phenomenon it describes, and evaluate it (Chang, Quintana, & Krajcik, 2009). Engaging in the full process led students to perform better on a test of chemistry achievement, as well as animation and interpretation quality, as compared to students who either just designed and created the animation, or designed, created, and interpreted the animation (Chang et al., 2009). In another example, students can use a simulation to model the behavior of ions near a cell membrane (Nichols, Hanan, & Ranasinghe, 2013). Students can modify the number of potassium or sodium channels and see how the simulation responds, and they also read prompting questions that indicate important elements to consider (Nichols et al., 2013). It was found that experimental students engaged in richer collaborative discussions and evidenced less misconceptions on a posttest than control students (Nichols et al., 2013)

Conceptual scaffolds can also use such tools as concept mapping to list important concepts in the material being learned and invite students to make connections between such concepts explicit through the use of connecting arrows (Chin, Dohmen, & Schwartz, 2013). Then, pedagogical agents (teachable agents) are asked questions, and the veracity of their answers depends on the appropriateness of the connections made in the concept map (Chin et al., 2013). This approach led experimental students to perform significantly better on tests of content knowledge and the ability to organize explanations according to categories (e.g., carnivore vs. herbivore) (Chin et al., 2013). In another example, *Belvedere* invited high school students to create claims, evidence elements, and premises, and to make connections among the different elements to create an evidence-based argument (Toth, Suthers, & Lesgold, 2002). Students who were invited to engage in concept mapping and to reflect on their work performed significantly better in overall reasoning than students who engaged in mapping without reflection, as well as students who wrote prose with and without reflection (Toth et al., 2002). In another example, elementary students conducting web-based inquiry were given a concept mapping tool along with guidance on how to link different concepts they encountered/were learning, and also guidance for searching and presentation design (MacGregor & Lou, 2004). Students who used the scaffolding recalled significantly more content from the investigation and also had significantly more creative and organized final presentations (MacGregor & Lou, 2004).

5.2.2 Strategic Scaffolding

Strategic scaffolding bootstraps a strategy that students can use to solve a problem (Hannafin et al., 1999; Reiser et al., 2001). From an activity theory perspective, this approach would still leave open the possibility for student agency in the application of the strategy, and possible modification thereof. This is because according to this framework, the semiotic process of building signs according to tools (e.g., scaffolds) is highlighted (Belland & Drake, 2013; Wertsch & Kazak, 2005). For example, a scaffold bootstrapped positive collaboration skills by providing a database of positive groupwork rules, inviting students to (a) create their own groupwork rules, (b) evaluate their group processes in light of the group rules they created, (c) discuss according to given discussion questions, and (d) self-evaluate the whole process (Ulicsak, 2004). Experimental students engaged in more lengthy discussions and exhibited greater reflection (Ulicsak, 2004). As another example, the *Connection Log* leads middle school students through a generic argument creation process (Belland, 2010) grounded in the persuasive theory of argumentation (Perelman & Olbrechts-Tyteca, 1958). This led lower-achieving experimental students (Belland, Glazewski, & Richardson, 2011) and average-achieving experimental students (Belland, 2010) to evaluate arguments significantly better than their control counterparts.

From an ACT-R perspective, the possibility for choice in the application of the strategy would be limited due to the desire to minimize unsuccessful practice (Anderson, 1983; Koedinger & Corbett, 2006). For example, in an intelligent tutoring system designed to help students learn LISP programming, the system provides a LISP programming task for students to do and a template for programming elements that need to be in the program (Corbett & Anderson, 2001). Students can type programming commands in a window, and the system checks the code and provides either immediate feedback, error flagging, or self-selected feedback (Corbett & Anderson, 2001). Such feedback was designed so as to promote speed in reaching the correct answers, consistent with the assumption in ACT-R that struggle is not desirable (Anderson et al., 1997). Students who received feedback made significantly fewer errors on the posttest than students who did not receive feedback (Corbett & Anderson, 2001).

From a knowledge integration perspective, choice may be allowed to the extent to which students' existing problem-solving schemas would be elicited and compared to provided normative strategies (Linn et al., 2003). But at the same time, allowing for student choice in the use of strategies is not an overt goal from the knowledge integration perspective in that the existence of normative strategies is posited.

5.2.3 Metacognitive Scaffolding

Metacognitive scaffolds invite and help students to evaluate their own thinking (Cuevas, Fiore, & Oser, 2002; Hannafin et al., 1999). Within scientific inquiry, important metacognitive processes include task definition and planning, monitoring and regulating, and reflection (Quintana, Zhang, & Krajcik, 2005). Metacognitive scaffolding can help students with several areas of the metacognitive process, including planning, monitoring and regulating, and reflection (Quintana et al., 2005). Metacognitive scaffolding focused on planning gives students tools for planning and also prompts them to consider the importance of the planning process (Azevedo, 2005; Quintana et al., 2005). Metacognitive scaffolding to enhance monitoring and regulating can focus on monitoring one's progress through the inquiry task according to a set of mileposts (Cuevas et al., 2002; Zhang & Quintana, 2012). Metacognitive scaffolding to enhance reflection can invite students to evaluate the quality of ideas and products generated according to rubrics (Cuevas et al., 2002; Quintana et al., 2005). For example, this may be by giving students criteria to make the evaluation and a forum in which to do so. A metacognitive scaffold invited middle school mathematics students to respond to questions emphasizing comprehension, connection, strategy, and reflection (Kramarski & Hirsch, 2003). Students who used the metacognitive scaffolding performed significantly better on a posttest of algebraic thinking than control students (Kramarski & Hirsch, 2003).

In another example, university students were given prompts encouraging them to stop and reflect on their answers to two questions regarding human immune systems, and a concept map they made with the pertinent concepts (Ifenthaler, 2012). These prompts were either generic or context-specific; students who received the generic prompts gained significantly more from pre- to posttest of domain-specific knowledge than students who received context-specific prompts and those in the control group (Ifenthaler, 2012).

Metacognitive scaffolds are not universally effective. For example, a metacognitive scaffold contained three tools to help college students during a computer literacy test—a project planning sheet, a tool to make connections in information, and a project reflection sheet (Su & Klein, 2010). Students who received metacognitive scaffolds performed significantly worse on a posttest than students who received conceptual scaffolds (Su & Klein, 2010). In another example, backward design strategic scaffolding used in conjunction with reflection rubrics helped high school science students judge the quality with which they collected data and other information, as well as the quality of their research reports and their peer reviews (Deters, 2008). Backward design scaffolding by itself led to a statistically significant and substantial effect on lab report quality, but when reflective prompts were used in conjunction with backward design scaffolding, there was no difference between the performances of experimental and control students (Deters, 2008).

5.2.4 Motivation Scaffolding

Motivation scaffolds primarily aim to enhance students' academic motivation toward the target content, defined as their willingness to deploy effort to carry out learning tasks (Tuckman, 2007; Wigfield & Eccles, 2000). This can be done through one of the following processes or a combination thereof: enhancing students' (a) expectancies for success, (b) perceptions of value in the completion of the target task, (c) perceptions of self-determination of behavior, (d) perceptions of mastery goals, (e) abilities to regulate academic emotions, and (f) perceptions of belongingness (Belland, Kim, et al., 2013). Strategies to do so include establishing attainment value, supporting productive attribution, and promoting the perception of optimal challenge (Belland, Kim, et al., 2013). Scaffolds have helped promote expectancy for success through inviting students to reflect on the efficacy of strategies (Davis & Linn, 2000; Herrenkohl & Cornelius, 2013). In addition, providing attributional feedback that guides middle school students to attribute failure to lack of effort and success to good strategy use has been found to lead to stronger motivation and self-concept among experimental students than among control students (Dresel & Haugwitz, 2008). Researchers deploy motivation scaffolds to increase engagement in the target content (Rienties et al., 2012) and to raise academic achievement (Belland, Kim, et al., 2013).

Historically, most designers aimed to create computer-based scaffolding that provided cognitive or motivational support, despite the importance of the integration of these two types of support (Belland, 2014; Belland, Kim, et al., 2013; Rienties et al., 2012). This approach leaves it entirely to one-to-one or peer scaffolding to provide the form of support that computer-based scaffolding does not. Motivation can make a big difference in students' performance in academic tasks, including the type of high-level tasks with which scaffolding is used (Belland, Kim, et al., 2013; Bereby-Meyer & Kaplan, 2005; Brophy, 1999; Giesbers, Rienties, Tempelaar, & Gijselaers, 2013; Perkins & Salomon, 2012). Expecting all cognitive support to be provided by computer-based scaffolds, and all motivational support by one-to-one scaffolding, or vice versa, is not likely the best choice. That is, in a typical classroom, there is one teacher, and that one teacher cannot work with all students at all times (Belland, 2012; Belland, Burdo, & Gu, 2015; Hogan & Pressley, 1997; Saye & Brush, 2002).

An alternative to assigning one scaffolding function to one-to-one scaffolding and another scaffolding function to computer-based scaffolding is to design scaffolding systems to provide redundancy in support such that students receive all needed support even if the teacher needs to work one-to-one with a struggling small group for an extended period of time (Puntambekar & Kolodner, 2005; Tabak, 2004). Such a scaffolding system can include computer-based scaffolding, peer scaffolding, and one-to-one scaffolding, and redundancy can be across and within scaffolding types (Belland, Gu, et al., 2013; Puntambekar & Kolodner, 2005). Providing such redundancy may allow students to be more likely to benefit from scaffolding support at the time they need it than if such support were only provided by one scaffolding mode (Puntambekar & Kolodner, 2005).

5.2.5 *Results from the Meta-Analysis*

The meta-analysis included 227 outcomes of conceptual scaffolding ($g=0.48$), 28 outcomes of metacognitive scaffolding ($g=0.42$), 75 outcomes of strategic scaffolding ($g=0.44$), and 3 outcomes of motivation scaffolding ($g=0.41$; Note: to be included, outcomes needed to be cognitive) (see Table 5.1; Belland, Walker, Kim, & Lefler, In Press). There were no statistically significant differences among scaffolding types, $p>0.05$. One interesting aspect of this finding is that it suggests that metacognitive scaffolding leads to strong learning outcomes. Metacognitive scaffolding has often been criticized, in part due to observations in the literature that students often do not use it (Belland, Glazewski, & Richardson, 2008; Oliver & Hannafin, 2000). But results suggest that it is as effective as other major scaffolding types. This provides a preliminary suggestion that rather than attempt to choose

Table 5.1 Table of results of moderator analyses on the effect of type of scaffolding intervention on cognitive outcomes

			95 % Confidence interval	
Level	*n* outcomes	Effect size estimate	Lower limit	Upper limit
Conceptual scaffolds	227	0.48	0.41	0.54
Metacognitive scaffolds	28	0.42	0.23	0.60
Motivation scaffolds	3	0.41	−0.02	0.85
Strategic scaffolds	75	0.44	0.36	0.53

a scaffolding type that is most effective and design accordingly, it is better to first decide on the nature of support students need, and then design the scaffolding support accordingly.

5.3 Context Specificity

In this section, I first describe what context specificity is with regard to scaffolding. Then, I address what the meta-analysis indicates about differences in effect sizes between context-specific and generic scaffolding.

5.3.1 What It Is

There has been much debate as to whether it is important to embed context-specific support in computer-based scaffolds. Much of this has to do with long-standing debates as to whether problem-solving skills are generic or context-specific; for an overview of the latter debate, see Perkins and Salomon (1989) and Schunn and Anderson (1999). Within one-to-one, teacher scaffolding, this question would be of little importance, as teachers can dynamically determine if such contextual support was needed. But given that computer-based scaffolding is designed before students use it, it is an important question to consider (Akhras & Self, 2002; Belland, 2014).

Computer-based scaffolding can be tailored to specific content or designed to be more generic in its approach (Belland, 2014; McNeill & Krajcik, 2009). For example, *ExplanationConstructor* was designed to be context specific (Sandoval & Reiser, 2004). Thus, all of its prompts included specific content related to the problem that students were addressing—microevolution among ground finches in the Galapagos Islands. As an example of a generic scaffold, the *Collaborative Concept Mapping Tool* was designed to facilitate groups' shared creation of concept maps in conjunction with units of different topics (Gijlers, Saab, Van Joolingen, de Jong, & Van Hout-Wolters, 2009).

One of the arguments advanced for using context-specific scaffolding is the idea that problem-solving skills are usually context bound, which emerged in part as a reaction against the practice of developing problem-solving heuristics based on such games as Towers of Hanoi and Missionaries and Cannibals (Perkins & Salomon, 1989). However, there is a strong evidence that problem-solving involves a mix of domain-specific and generic skills (Klahr & Simon, 1999; Molnár, Greiff, & Csapó, 2013; Perkins & Salomon, 1989; Schunn & Anderson, 1999). In this way, it is important to consider the nature of the subskill that one wishes to support through scaffolding in order to decide whether to use context-specific or generic scaffolding (Belland, Gu, et al., 2013).

There is not a large amount of research that directly compares the effectiveness of generic and context-specific scaffolds. A pilot meta-analysis found no difference in effect sizes between context-specific and generic scaffolds (Belland, Walker, Olsen,

Table 5.2 Results of moderator analyses on the effect of type of context specificity on cognitive outcomes

Level	n outcomes	Effect size estimate	95 % Confidence interval	
			Lower limit	Upper limit
Context-specific	273	0.46	0.41	0.52
Generic	60	0.48	0.35	0.60

& Leary, 2015). However, there is some evidence about specific questions related to context-specific and generic scaffolding. For example, there is some evidence that generic prompts for reflection promote better science learning among middle school students than context-specific ones (Davis, 2003). However, reflection is not the only process supported by scaffolding. There is also evidence that synergy is promoted when teachers provide one-to-one scaffolding from the perspective of a generic argumentation framework and computer-based scaffolds provide context-specific argumentation scaffolding, thereby maximizing middle school students' learning of argumentation (McNeill & Krajcik, 2009).

Rather than simply declaring that generic or context-specific scaffolding is the best, a better approach may be to consider how to combine context-specific and generic scaffolding, as well as one-to-one and computer-based scaffolding, according to the types of skills to be supported and the inherent strengths of a generic approach versus that of a context-specific approach, and that of a one-to-one versus a computer-based approach (Belland, Gu, et al., 2013). That is, one can consider how to create a portfolio of generic and context-specific scaffolding that optimally supports student learning and performance.

Beyond the suitability of scaffolding strategies for supporting specific skills, there are considerations regarding scalability. If a scaffold is entirely context-specific, then all of its instructional messages are inextricably tied to the specific content with which students are working in the target unit (Belland, Gu, et al., 2013). As such, the scaffold can only be used in the context of the target unit. Generic scaffolds use language that is not tied to the target unit such that they can be used in conjunction with other units.

5.3.2 Results from Meta-Analysis

The meta-analysis included approximately 4.5 times as many outcomes from studies that investigated context-specific scaffolds ($n=273$) than from studies that investigated generic scaffolds ($n=60$) (see Table 5.2; Belland, Walker, Kim, & Lefler, In Press). When one considers that 82 % of included outcomes in the meta-analysis were associated with context-specific scaffolding, it seems clear that scaffolding designers are choosing to design context-specific scaffolding more often than generic scaffolding. This may be based on the idea that the type of strategies that one tried to promote through scaffolding (e.g., problem-solving strategies) are inherently context-specific and cannot be performed or learned sufficiently without an adequate base of conceptual knowledge. But there was no significant difference between the average effect sizes when generic scaffolding ($g = 0.48$) and context-specific scaffolding ($g = 0.46$) were used, $p = 0.778$. This suggests that arguments that problem-solving and other strategies are context-specific and need to be supported by context-specific scaffolding are not supported by the corpus of empirical evidence on computer-based scaffolding in STEM education, or at least that which met the inclusion criteria (namely, met scaffolding definition, had an experimental and a control group, and contained sufficient information to calculate an effect size). That is, students seem to do equally well whether domain knowledge is embedded in the scaffolding or not. Thus, scaffolding designers can choose to use generic or context-specific scaffolding based on a determination of which strategy works best under the constraints of the learning context, rather than a consideration of which strategy is the most effective (Belland, Gu, et al., 2013).

5.4 Customization Presence or Absence

One of the biggest sticking points as the metaphor of scaffolding was applied to computer-based tools was the issue of contingency—namely, whether scaffolding was added, faded, or added and faded based on an estimation of the current ability of the student. As computer-based scaffolding was introduced, much lacked anything in the way of contingency, leading some authors to question whether the tools could be called scaffolding at all (Pea, 2004; Puntambekar & Hübscher, 2005). Indeed, Pea (2004) noted that such tools may be better described as part of distributed cognition, defined as a system in which information and an executive function are distributed among various individuals and tools such that no one entity carries out the entire extent of cognition required by the task (Belland, 2011; Giere, 2006). Most such arguments have been voiced by researchers from the activity-theory- and knowledge-integration-informed scaffolding traditions. This is perhaps because fading and adding is consistently applied in ACT-R-informed scaffolding (Koedinger & Aleven, 2007).

A closer look at the nature of scaffold fading, adding, and fading/adding is warranted. Fading refers to gradually removing support as students gain skill (Collins et al., 1989; Wood, Bruner, & Ross, 1976). One can base fading on dynamic assessment of students' capabilities, though fading in much computer-based scaffolding is based on self-selection and fixed intervals. Fading can involve but is not limited to gradually transitioning students to a less supportive/directive form of support, lessening the frequency of prompts, and lessening the specificity of feedback. For example, one scaffold for high school students progressed from providing sentence starters in the body of a text box to a simple prompt to formulate sources to no prompt at all; this progression happened on a fixed schedule (Raes, Schellens, De Wever, & Vanderhoven, 2012).

Adding support refers to increasing the strength or frequency of support as performance indicators show that students need more support (Koedinger & Aleven, 2007). As with fading, this should be implemented on the basis of dynamic assessment, though it is often based on self-selection (Koedinger & Aleven, 2007).

Table 5.3 Results of moderator analyses on the effect of customization on cognitive outcomes

			95 % Confidence interval	
Level	*n* outcomes	Effect size estimate	Lower limit	Upper limit
Fading	12	0.62	0.38	0.87
Adding	62	0.46	0.35	0.56
Fading/adding	43	0.50	0.36	0.63
None	216	0.46	0.39	0.52

Adding can involve providing more directive support, providing additional feedback of a different nature, and increasing the frequency of prompts. For example, the *Mobile Knowledge Constructor* invited students to find a plant in a garden (Chu, Hwang, & Tsai, 2010). It then asked questions about features of the target plant. If students answered incorrectly, it guided them to another plant that has the mistaken feature. After studying the new plant, students needed to answer the question they missed again.

Fading and adding is simply the combination of fading and adding within the same scaffolding treatment. As with fading and adding, fading/adding should be performed on the basis of dynamic assessment. Accordingly, fading occurs when performance indicates that students are gaining sufficient skill to perform the target task independently, whereas adding occurs when students are not on track to improve as rapidly as desired. For example, a scaffolding system broke content to be learned into different blocks (S. Li, 2001). For each block, there were four levels of support possible: no support, provide hint, provide example, and provide answer. Students started out at the hint level. In the system-controlled version, if they answered correctly, they would be moved down to no support. If they answered incorrectly, then they would be provided an example, and so on.

No fading/adding means that there is no customization of scaffolding. In other words, scaffolding is the same throughout students' engagement with the central problem. Researchers often argue that not-fading/adding can lead to overscripting, a situation in which scaffolding is provided when it is in fact not needed, thereby conflicting with existing mental models of how to address the targeted problem (Dillenbourg, 2002). This in turn is said to lead to weaker learning outcomes.

5.4.1 Results from Meta-Analysis

It makes sense to take a step back from the theoretical arguments to see if scaffold customization actually impacts cognitive outcomes. The scaffolding meta-analysis covered outcomes of scaffolds that incorporated several variations of contingency—fading ($n=12$), adding ($n=62$), fading and adding ($n=43$), as well as no fading or adding ($n=216$) (see Table 5.3) (Belland et al., In Press). Thus, the majority of outcomes were associated with no fading or adding (64.9 %). Of the included outcomes, 16.5 % were associated with scaffolding that incorporated fading in some way, either just fading, or fading and adding. This is close to what was found in the review of scaffolding research by Lin et al. (2012), who found that 9.3 % of the reviewed studies incorporated fading. And it is generally consistent with the lamentations of scaffolding scholars (Pea, 2004; Puntambekar & Hübscher, 2005). This appears to confirm that fading is rarely incorporated in scaffolding.

There was no significant difference in cognitive outcomes among the different contingency types. This is interesting in that authors often lament the lack of attention to scaffolding customization. But the results indicate that the presence or the type of scaffolding customization does not influence cognitive outcomes. Simply put, from a cognitive outcome standpoint, incorporating fading, adding, or fading/adding made no difference. This suggests that researchers might be best served considering other scaffolding factors in their quest to maximize student learning from scaffolding.

5.5 Customization Basis

While in the original scaffolding definition, customization was based on a teacher's assessment of students' performance indicators (Wood et al., 1976), customization of computer-based scaffolding has not always been performance based. When scaffolding is customized based on performance indicators, the scaffolding engages in dynamic assessment of student performance. For example, students may need to complete a quiz. Based on their score, scaffolding is customized. This is often done in intelligent tutoring systems (Koedinger & Corbett, 2006).

Other strategies used as the basis of the customization of computer-based scaffolding included setting scaffolding to reduce in strength according to fixed time intervals (fixed fading) (Dori & Sasson, 2008; McNeill, Lizotte, Krajcik, & Marx, 2006; Philpot, Hall, Hubing, & Flori, 2005) or when students click a button (self-selected fading) (Clark, Touchman, Martinez-Garza, Ramirez-Marin, & Skjerping Drews, 2012; Metcalf, 1999; Renkl, 2002). Customization based on fixed time intervals means that the scaffold designer determines time intervals after which scaffolding should be faded or added. Once the time interval is passed, the scaffolding would be added or faded automatically. Self-selection means that a button is provided with which students can request hints (adding) or request that scaffolding be removed (fading). For example, adding scaffolding (hints) has also been linked to pressing buttons in intelligent tutoring systems (Koedinger & Aleven, 2007), and fading has been controlled by students who press a button indicating that they perceive that they do not need the scaffolding any longer (Metcalf, 1999). The rationale for the use of self-selection in adding in intelligent tutoring systems is to avoid unproductive struggle, and it is thought that students can recognize that they are struggling too much (Koedinger & Aleven, 2007). Similarly, in self-selected fading, it is thought that learners can accurately gauge the extent to which they need scaffolding assistance at a given point in a learning task (Metcalf, 1999). This relies on learners to make good instructional decisions, which they often struggle to do (Williams, 1996). Furthermore, fixed and self-selected customization does not appear to fit the original definition and may not have been performed on the basis of performance characteristics (Belland, 2011).

Sometimes, scaffolding can be customized on the basis of performance indicators and self-selection. For example, students may self-select a level of scaffolding that they want before engaging with the scaffold; as they engage in the system, the system may provide feedback and suggestions to adjust the self-selected scaffolding level on the basis of performance characteristics (Cheng et al., 2009). Intelligent tutoring systems often provide feedback on the basis of performance indicators, but students can also request more help by clicking a hint button. If the first hint does not help enough, the student can click the hint button again to get a more detailed hint, until eventually he/she is given the solution (Koedinger & Aleven, 2007). Intelligent tutoring systems based on the ACT-R model of cognition guide students through a task using several strategies, including providing choices on what methods to use to solve the target problem, feedback on what students do, and hints on how to accomplish certain steps (Koedinger & Aleven, 2007; Koedinger & Corbett, 2006; VanLehn, 2011). According to ACT-R, complex cognitive domains can be seen as a set of production rules and declarative knowledge, and such production rules can be learned independently (Anderson, 1983; Anderson et al., 1997; Koedinger & Aleven, 2007). Hints are designed to reduce the amount of unproductive practice in which students engage, which ACT-R posits as an impediment to learning (Anderson, 1990; Anderson et al., 1997). Sometimes, hints are requested by students, and sometimes they are provided based on the intelligent tutoring system's estimation of student ability. Intelligent tutoring systems also keep track of students' abilities through knowledge tracing (Koedinger & Aleven, 2007; Koedinger & Corbett, 2006). In this way, they estimate whether students know or do not know the production rule under study. Through knowledge tracing, an intelligent tutoring system can estimate when a student is ready to proceed to the next unit and select problems of appropriate difficulty (Koedinger & Aleven, 2007; Koedinger & Corbett, 2006). It can also determine when a student needs more or less support, and adjust the support accordingly.

Preliminary meta-analyses of scaffolding indicated that fixed fading led to an average effect that was not significantly different from zero (Belland, Walker, Kim, & Lefler, 2014; Belland, Walker, et al., 2015). Linking customization to self-selection poses challenges as well. In the case of intelligent tutoring systems, hints usually become successively more detailed/supporting, causing some students to game the system by pressing the button multiple times until they get the answer (Koedinger & Aleven, 2007). Furthermore, computer-based scaffolding rarely incorporates feedback (Belland, 2014).

5.5.1 Results from Meta-Analysis

Again, taking a step back from the theoretical arguments, it is important to examine whether the basis by which scaffolding is faded, added, or faded and added influences cognitive outcomes. Of the outcomes in which scaffolding customization was

Table 5.4 Results of moderator analyses on the effect of customization schedule on cognitive outcomes

Level	*n* outcomes	Effect size estimate	95 % Confidence interval	
			Lower limit	Upper limit
Performance-based	63	0.47	0.35	0.60
Fixed	13	0.62	0.42	0.82
Self-selected	41	0.45	0.35	0.55
None	216	0.45	0.39	0.52

present, 53.8 % involved performance-based customization, 35 % involved self-selection, and 11.1 % involved fixed customization (See Table 5.4; Belland et al., In Press). Of note, many scaffolding interventions that incorporated performance-based customization were embedded in intelligent tutoring systems. In such cases, even though there was often both performance-based fading and self-selected adding, the scaffold was classified as performance-based since the performance-based customization would always be present and theoretically always happen, while self-selected adding would only happen if students clicked the hint button. Future research may attempt to disentangle such combinations of scaffolding bases to tease apart the effect of these different scaffolding components. However, this would be difficult as one would likely need to be able to attribute outcomes to specific scaffolding components for which customization was performance-based, and other outcomes to other outcomes that were self-selected. The inclusion of such outcomes that can be easily attributed to separate scaffolds is quite rare.

There were no statistically significant differences among the scaffolding customization bases. This means that there were no differences between performance-based customization, fixed customization, self-selected customization, and no customization. This largely flies in the face of the generally accepted consensus among scaffolding scholars that scaffolding customization is better than no scaffolding customization, and that performance-based customization is the best of all. From a statistical standpoint, there was no difference in cognitive outcomes. This is very interesting. Of course, further research is needed to understand the role of scaffolding customization and scaffolding customization bases in STEM learning. For example, only cognitive outcomes were included; there may be differences in terms of motivation or self-direction. This finding conflicts with the findings from a pilot scaffolding meta-analysis that indicated that when scaffolding was not faded, effect sizes were higher than when scaffolding was faded on a fixed schedule (Belland, Walker, et al., 2015). In yet another prior scaffolding meta-analysis, fixed fading led to an effect size that was not significantly greater than zero, while not-fading led to an effect size that was significantly greater than zero (Belland et al., 2014).

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Chapter 6
Conclusion

Abstract In this chapter, I conclude this book on computer-based scaffolding in science, technology, engineering, and mathematics (STEM) education. I note the overall effect size point estimate for scaffolding—$g = 0.46$—and compare that to other effect size estimates in the literature. I summarize the wide variation in contexts in which and learner populations among which scaffolding is used, as well as note the characteristics along which the magnitude of scaffolding's impact does not vary—contingency, generic versus context specific, and intended learning outcome—as well as characteristics along which it does—problem-centered model with which scaffolding is used, and grade level and learner characteristics. I also note areas in which more research is needed—motivation scaffolding, scaffolding for students with learning disabilities, and scaffolding in the context of project-based and design-based learning.

Keywords Content learning · Context specificity · Problem-centered instruction · Scaffolding customization · Scaffolding strategy · STEM disciplines

6.1 Overall Implications

Despite the attempt by Kirschner, Sweller, and Clark (2006) to posit problem-centered instructional approaches as failures due to their purported lack of instructional guidance, it has been seen in this book that problem-centered instruction paired with computer-based scaffolding is quite effective in promoting strong cognitive outcomes. Scaffolding leads to effects that were significantly greater than zero and practically important across the concept, principles, and application assessment levels (Belland, Walker, Kim, & Lefler, In Press; Sugrue, 1995). As strength across such a wide range of assessment levels was not found in meta-analyses of problem-centered instructional approaches by themselves (e.g., Albanese & Mitchell, 1993; Gijbels, Dochy, Van den Bossche, & Segers, 2005; Walker & Leary, 2009), one can conclude that it is the instructional support of computer-based scaffolding that leads to the strong outcomes.

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Scaffolding used in the context of problem-centered instruction led to an average effect size of $g = 0.46$ on cognitive outcomes. This is in line with results from prior meta-analyses, which indicated overall effect sizes of $g = 0.53$ (Belland, Walker, Olsen, & Leary, 2015) and $g = 0.44$ (Belland, Walker, Kim, & Lefler, 2014) for computer-based scaffolding in science, technology, engineering, and mathematics (STEM) education. It is below the effect size estimate for step-based intelligent tutoring systems ($ES = 0.76$) found in a recent review (VanLehn, 2011), but this is to be expected as our review covered a much wider variety of scaffolding treatments. Briefly, computer-based scaffolding has a substantial impact on cognitive outcomes. This is consistent with prior research (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Belland et al., 2014; Belland, Walker, et al., 2015; Dochy, Segers, Van den Bossche, & Gijbels, 2003; Gijbels et al., 2005; Hmelo-Silver, Duncan, & Chinn, 2007; Kuhn, 2007; Schmidt, van der Molen, te Winkel, & Wijnen, 2009; Strobel & van Barneveld, 2009; Swanson & Lussier, 2001; Walker & Leary, 2009) and also reflects well on the considerable investment that has been made developing and studying scaffolding.

Although the intended learning outcomes of computer-based scaffolding include both content-learning and the development of higher-order thinking skills, it is worthwhile to compare its average effect size with that of a wider range of instructional interventions designed to enhance critical thinking skills, and educational technology interventions as a whole. Computer-based scaffolding's effect ($g = 0.46$) is greater than the average effect size of educational technology interventions designed to support direct instruction ($ES = 0.31$) found in a synthesis of meta-analyses of educational technology interventions conducted over the course of 40 years (see Fig. 6.1; Tamim, Bernard, Borokhovski, Abrami, & Schmid, 2011).

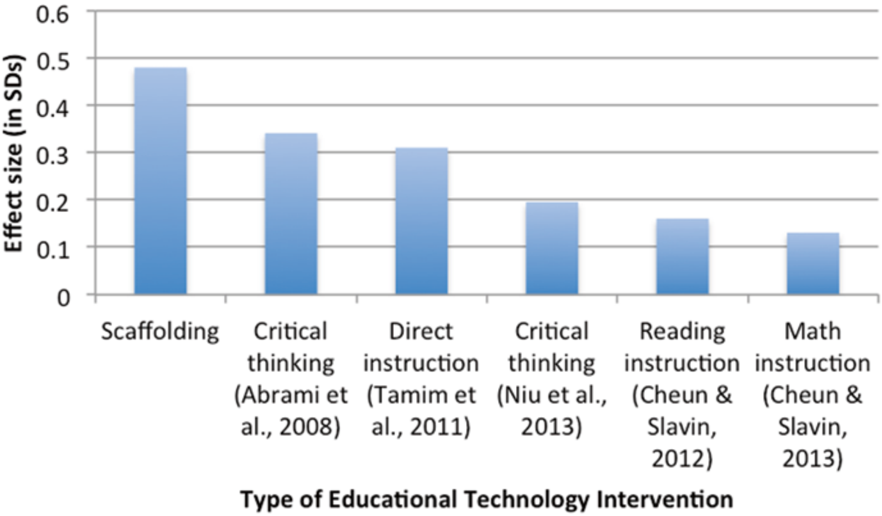

Fig. 6.1 Computer-based scaffolding's effect size estimate as compared to that of related educational technology interventions

It is also higher than the effect size estimates of interventions designed to increase critical thinking abilities: *ES*=0.195 (Niu, Behar-Horenstein, & Garvan, 2013) and *ES*=0.341 (Abrami et al., 2008). It is also higher than the average effect size of educational technology applications designed for mathematics education (*ES*=0.13; Cheung & Slavin, 2013) and that of educational technology applications designed for reading instruction (*ES*=0.16; Cheung & Slavin, 2012) found in recent reviews. Furthermore, the average effect size for computer-based scaffolding is higher than the median effect size among meta-analyses of interventions in psychological research ($g=0.324$; Cafri, Kromrey, & Brannick, 2010). Briefly, the magnitude of the effect of computer-based scaffolding on cognitive outcomes is substantial when compared to instructional interventions that seek to influence similar outcomes, and also compared to other educational technology interventions and interventions in psychological research.

Computer-based scaffolding includes a wide variation of interventions, ranging from scaffolding embedded in intelligent tutoring systems, which contain all material to be encountered by students and which fade scaffolding based on a comparison of student performance with a model of an idealized student and allow students to add scaffolding by clicking a hint button (Koedinger & Corbett, 2006; Means & Gott, 1988) to tools used when investigating problems in the outside world that often do not involve fading or adding (Pea, 2004; Reiser, 2004). This large variation in scaffolding can be traced to the different theoretical frameworks (i.e., activity theory (Leont'ev, 1974; Luria, 1976; Vygotsky, 1978), Adaptive Character of Thought—Rational (ACT-R; Anderson, 1983; Anderson, Matessa, & Lebiere, 1997), and knowledge integration (Linn, 2000; Linn, Clark, & Slotta, 2003)) that were integrated into the relatively atheoretical initial conceptualization of scaffolding (Wood & Wood, 1996). Each of these theoretical frameworks has different views on the nature of learning and the goal of instruction. Still, the characteristics on which scaffolding informed by these different theoretical frameworks varies—contingency, generic versus context-specific, and intended learning outcome—did not explain any significant differences in cognitive outcomes. This suggests that the effect of scaffolding on cognitive learning outcomes is robust to different intended learning outcomes and the choice of whether or not to embed content knowledge in scaffolding, and is largely robust to the presence or absence of scaffolding customization as well as customization bases.

6.2 How the Meta-Analysis Responds to Persistent Debates in the Scaffolding and Problem-Centered Instruction Literature

This book presents some interesting answers to questions regarding scaffolding customization, the role of context-specific information in scaffolding, and whether scaffolding should be geared toward promoting enhanced content learning or higher-order thinking abilities. I certainly do not consider such questions to be answered definitively, as there is much to be learned when considering these findings alongside findings of empirical studies that were not eligible for inclusion in the meta-analysis. Such may be accomplished through the use of meta-synthesis (Bondas & Hall, 2007; Finfgeld, 2003; Thorne, 2004) and other synthesis efforts. Such further work can help to further address these questions and help scaffolding developers and researchers learn the most effective scaffolding strategies.

6.2.1 Scaffold Customization

Scaffolding scholars from the various scaffolding theoretical traditions have long posited scaffolding customization as a necessary attribute of scaffolding (Collins, Brown, & Newman, 1989; Pea, 2004; Puntambekar & Hübscher, 2005). This was clearly an important part of the original scaffolding definition; scaffolding customization unfolded as teachers dynamically assessed students' current abilities and adjusted the support that was given accordingly. Scholars from the intelligent tutoring systems tradition have long called for the use of fading and adding (Aleven, Stahl, Schworm, Fischer, & Wallace, 2003; Koedinger & Aleven, 2007), while scholars from the knowledge integration and activity theory traditions have called for the use of fading (Collins et al., 1989; McNeill, Lizotte, Krajcik, & Marx, 2006; Pea, 2004; Puntambekar & Hübscher, 2005). Indeed, some scholars suggested that interventions that do not include fading cannot be called scaffolding (Pea, 2004; Puntambekar & Hübscher, 2005). The count of outcomes in which scaffolding was faded or added versus when scaffolding was neither added nor faded indicated that the majority of outcomes were associated with no fading or adding (64.9 %), which is consistent with prior research (Lin et al., 2012; Pea, 2004; Puntambekar & Hübscher, 2005). But the meta-analysis suggests that scaffold customization does not influence cognitive outcomes. Further research is needed to fully understand the role of scaffold customization in promoting learning.

Cognitive outcomes are only one way to characterize the success (or lack thereof) of an instructional intervention/feature. Other ways include attitudinal and affective outcomes and the capacity of the intervention to foster transfer, neither of which were the focus of the underlying meta-analysis of this book. Indeed, one of the arguments in favor of fading holds that providing scaffolding support when it is not needed can undermine motivation, thereby decreasing learning and performance (Dillenbourg, 2002). Motivation is a very important influence on learning (Belland, Kim, & Hannafin, 2013; Fredricks, Blumenfeld, & Paris, 2004; Wigfield & Eccles, 2000), and so investigating the influence of scaffolding customization (or lack thereof) on motivation, and consequently on achievement, is important and warrants future research.

One can also examine the extent to which scaffolding leads to transfer, including students' preparation for future learning (Bransford & Schwartz, 1999) and their ability to recognize similarities between the learning context and new contexts in which the learning can be applied (Lobato, 2003). Transfer is clearly an important goal of problem-centered instruction and forms one of the key pillars in the rationale for such approaches (Hmelo-Silver, 2004). Does scaffolding customization influence transfer? This is an empirical question that warrants future research.

6.2.2 Problem-Centered Instruction and Content Learning

One of the persistent criticisms of problem-centered instructional models is that they do not do a good job in promoting concept-level learning (Kirschner et al., 2006). The thinking goes that problem-based learning does a better job than lecture at promoting learning at the principles and application levels but does not do as well at promoting concept-level learning (Albanese & Mitchell, 1993; Berkson, 1993). This is borne out in most meta-analyses of problem-based learning that break learning down by assessment level (Albanese & Mitchell, 1993; Gijbels et al., 2005; Kalaian, Mullan, & Kasim, 1999; Vernon & Blake, 1993; Walker & Leary, 2009), and has been found to be consistent outside of medical education (Walker & Leary, 2009). One exception to this trend is that problem-based learning seems to tend to lead to stronger long-term concept learning than lecture (Dochy et al., 2003; Strobel & van Barneveld, 2009).

One review found mixed results on inquiry-based learning's influence on concept learning, finding that student concept learning was predicted by the extent to which students needed to think actively and draw conclusions from data, rather than by the simple use of inquiry-based learning (Minner, Levy, & Century, 2010). Another review indicated that when inquiry-based learning aims at promoting epistemic and conceptual learning, effect sizes tend to be quite low ($ES=0.19$) as compared to studies that focused squarely on epistemic learning goals ($ES=0.75$) or on procedural, epistemic, and social goals ($ES=0.72$; Furtak, Seidel, Iverson, & Briggs, 2012).

In this meta-analysis, scaffolding used in the context of problem-centered instructional models led to average effect sizes at the concept, principles, and application levels of $g=0.40$, $g=0.51$, and $g=0.44$, respectively. These are all substantial effect sizes and mean that scaffolding leads to strong learning outcomes across the three assessment levels (Sugrue, 1995). The findings suggest that by employing computer-based scaffolding along with problem-centered instructional models, one can erase the former liability of problem-centered instructional models—poor concept learning. This makes sense when one considers that inquiry-based learning led to strong effect sizes on content learning when students needed to engage in active thinking (Minner et al., 2010). Scaffolding promotes active thinking on the part of students, and often encourages them to draw conclusions from data (Belland, 2014; Quintana et al., 2004; Reiser, 2004).

6.2.3 Context Specificity

Much work on scaffolding in science has focused on context-specific scaffolding due to thoughts that (a) scientific problem-solving is highly context specific (Abd-El-Khalick, 2012; McNeill & Krajcik, 2009; Perkins & Salomon, 1989) and (b) any problem-solving strategy that involves any domain-specific knowledge is itself domain specific (Smith, 2002). Furthermore, there are arguments that one does not need to teach generic skills, based on a premise that individuals will simply pick up the generic skills they need through everyday life (Tricot & Sweller, 2013). That the majority of computer-based scaffolding is context specific was confirmed by the fact that 82 % of the outcomes included in the meta-analysis were associated with context-specific scaffolding. The arguments above against scaffolding generic processes appear to be tenuous arguments, and one would be better served to look at the empirical evidence to decide whether generic or context-specific scaffolding is more effective.

Much evidence indicates that scientific problem-solving in fact incorporates a mix of domain-specific and generic processes (Klahr & Simon, 1999; Molnár, Greiff, & Csapó, 2013; Perkins & Salomon, 1989; Schunn & Anderson, 1999). For example, evaluating sources can involve domain-specific knowledge, but the underlying strategy can be considered generic (Smith, 2002). There is not a large amount of empirical work addressing the relative effectiveness of generic and context-specific scaffolding. But we addressed it in the meta-analysis, finding no differences in cognitive outcomes between generic and context-specific scaffolding. Therefore, one may envision the need for a mix of generic and context-specific scaffolding that can allow the strengths of each scaffolding type to complement each other (Belland, Gu, Armbrust, & Cook, 2013).

6.2.4 Higher-Order Thinking Skills Versus Content Knowledge

Scaffolding has been used to promote the development of higher-order thinking skills (Belland, Glazewski, & Richardson, 2011; Belland, Gu, Armbrust, & Cook, 2015; Kim & Hannafin, 2011) and enhanced content knowledge (Chang & Linn, 2013; Davis & Linn, 2000)—two seemingly disparate instructional goals. These differences in instructional goals can be linked to differences in the theoretical bases to which scaffolding is tied. These differences in theoretical bases lead to real differences in scaffolding strategies, such as the use of adding and fading (Koedinger & Aleven, 2007) versus fading (Pea, 2004; Puntambekar & Hübscher, 2005), differences in intended learning outcomes, and differences in contexts of use. Such a disparity in intended learning outcome may lead one to think that these are qualitatively different interventions. Yet, the scaffolding definition that noted that scaffolding needs to extend and enhance student abilities as they engage in authentic problem-solving was carefully applied. Meta-analysis indicated that the two scaffolding types lead to effect sizes that were statistically the same.

6.2.5 *Scaffolding Strategy*

Scaffolding can incorporate a variety of approaches according to what processes it aims to support in students, including conceptual, strategic, metacognitive, and motivational scaffolding (Belland, Kim, et al., 2013; Hannafin, Land, & Oliver, 1999). Designers of computer-based scaffolding often chose to support either motivation or cognition (Belland, Kim, et al., 2013), and the effectiveness of metacognitive scaffolding has often been questioned (Belland, Glazewski, & Richardson, 2008; Oliver & Hannafin, 2000). But the meta-analysis indicated that there were no differences in cognitive student outcomes on the basis of scaffolding strategy. Certainly, further research is needed to ascertain if the integration of support for motivation and cognition in the same scaffold leads to stronger learning outcomes than when such support is separated.

6.2.6 *Summary*

Briefly, decisions about whether to (a) include context-specific content or not, (b) target higher-order thinking abilities or content knowledge, and (c) fade, add, or fade and add scaffolding and on what basis can be made without fear of adversely impacting learning outcomes. Rather, such decisions can be made in the context of learning goals and what is known about the target learner population. And further research is needed to determine if these conclusions apply to education areas other than STEM.

6.3 Other Interesting Findings

6.3.1 *Scaffolding's Effectiveness in Different STEM Disciplines*

It was interesting that computer-based scaffolding was equally effective, statistically, in science, technology, engineering, and mathematics. This suggests that scaffolding is a highly effective intervention that is appropriate for use with a wide range of authentic problems across STEM. Clearly, addressing authentic problems is a crucial skill throughout STEM. It would be unwise to think that students will automatically have the skills to be able to do so, or that if they learn declarative content, they will figure out how to apply the content to authentic problems. Furthermore, there is a need for more primary research to be done on scaffolding in engineering and mathematics education; such further research is needed to obtain a more precise estimate of the effect of scaffolding used in the context of mathematics and engineering education. Certainly, computer-based scaffolding would seem to fit well with the types of goals that instructors often have in mathematics and engineering education—to use the tools of the respective disciplines to model and solve problems, both through conceptual solutions and the design of products (Brophy, Klein, Portsmore, & Rogers, 2008; Carr, Bennett, & Strobel, 2012; Lesh & Harel, 2003; Schoenfeld, 1985).

6.3.2 Scaffolding's Effectiveness by Grade Level

Next, it was interesting that scaffolding has come to be used at many different educational levels, and the largest effect sizes were among graduate and college learners. This is indeed a large expansion of an instructional method originally proposed to describe how adults could help toddlers learn to construct pyramids with wooden blocks. It also brings to light an important consideration that the distance between a more capable other and the learner in graduate education is much less than in preschool. There is an expectation that preschool students think about problems in qualitatively different ways than do adults (Inhelder & Piaget, 1955), and so the metaphor of scaffolding in which a more capable other extends and enhances student cognition makes intuitive sense. But the hope is that graduate students gradually begin to think about pertinent problems in the same general manner as their professors. In this way, it may be difficult to apply the scaffolding metaphor in an intuitive manner to graduate education. Further research is needed to explore the role of scaffolding in graduate education and how it differs from scaffolding used in the context of other education levels.

6.4 Directions for Future Research

This book also suggests directions for future research. In particular, more research is needed on motivation scaffolding and scaffolding in the context of design-based learning and project-based learning. With the exception of design-based learning, these were all associated with particularly large effect size point estimates, but one could not have great confidence in the estimates due to a small sample size. For design-based learning, the point estimate was low relative to other contexts of use.

Supporting motivation through scaffolding has often been an afterthought when one desires to enhance cognitive skills (Belland, Kim, et al., 2013; Rienties et al., 2012), and this led us to find only one article that met the inclusion criteria, among which was that the student had to measure cognitive outcomes. But its outcomes had very large effect sizes. Furthermore, theory suggests that scaffolds that support motivational and cognitive aspects of student work are likely to be more effective than scaffolds that focus solely on cognitive factors (Belland, Kim, et al., 2013). This may indicate that (a) if more scaffolding is designed to enhance motivation alongside cognitive outcomes, one may find very strong effects, and (b) researchers would be advised to measure cognitive outcomes resulting from the use of existing motivation scaffolds (Brophy, 1999).

In brief, all of these areas would seem to benefit from more primary research, both to improve the precision of estimates of scaffolding's effect on cognitive outcomes and to potentially learn more about a promising way to help students develop the skills they need to succeed in potentially authentic instructional approaches (Belland, 2014; Hmelo-Silver et al., 2007) and the twenty-first century workforce (Carnevale & Desrochers, 2003; Gu & Belland, 2015).

Finally, it is important to investigate the relative impact of scaffolding characteristics and contexts of use on cognitive outcomes in non-STEM areas (Brush & Saye, 2001; Proctor, Dalton, & Grisham, 2007). These are clearly important learning outcomes, and enhancing these would not only help students be better prepared for careers in STEM but also for the twenty-first century economy in general (Gu & Belland, 2015).

Instructional scaffolding is an effective intervention that can help students perform a half a standard deviation higher than they would have been able to otherwise (Belland et al., In Press, 2014; Belland, Walker, et al., 2015; VanLehn, 2011). Scaffolding led to effects that were statistically greater than zero across education levels ranging from primary to adult. The effect size estimate for middle-level learners was lower than that of adult students but still compared favorably to similar instructional interventions. Scaffolding also led to effect size estimates that were statistically significantly greater than zero across a range of learner populations, from underrepresented and underperforming to low income, traditional, and high performing. However, underperforming students had a lower effect size estimate than traditional students. Scaffolding also had consistently positive effects among instructional models with which it is used. Furthermore, scaffolding led to positive effect size estimates across science, technology, engineering, and mathematics education. Scaffolding's sizable impact on cognitive outcomes was largely consistent across assessment levels, with the caveat that when learning was assessed at the principles level, effect sizes were higher than when assessed at the concept or application level.

Scaffolding had a positive effect size estimate across customization type (i.e., fading, adding, fading/adding, or none), customization basis (i.e., performance based, self-selected, and none), or whether or not context-specific information was embedded in the scaffolding. There were no significant differences among these moderators. Furthermore, the effect size estimate was consistently positive across scaffolding intervention types (i.e., conceptual, metacognitive, strategic, and motivation), and there were no significant differences in this categorization.

6.5 Conclusion

Computer-based scaffolding is a highly effective intervention that leads to strong effect sizes that are statistically significantly greater than zero across contexts of use, intended learning outcomes, and scaffolding characteristics (Belland et al., In Press). Scaffolding is particularly well positioned to help students succeed in the problem-centered instructional approaches encouraged by the Next Generation Science Standards and Common Core Standards (Achieve, 2013; Krajcik, Codere, Dahsah, Bayer, & Mun, 2014; McLaughlin & Overturf, 2012; National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010; National Research Council, 2012). It can do this by extending students' abilities in the following areas: argumentation (Belland, 2010; Cho & Jonassen, 2002), modeling (Buckland & Chinn, 2010; Fretz et al., 2002), problem-solving (Ge & Land, 2003; Raes, Schellens, De Wever, & Vanderhoven, 2012), and forming coherent mental models to describe natural phenomena (Clark & Linn, 2013; Linn, 2000). As such, computer-based scaffolding is a timely intervention that raises the likelihood that problem-centered models will be successful. Research outlined in this book can contribute to an understanding of the scaffolding goals, strategies, and contexts of use that are associated with the strongest cognitive learning outcomes.

Results indicate differences in effect sizes based on several characteristics. But in most of these cases, effect sizes for the levels of the characteristic that was associated with lower effect size estimates were also substantial and significantly greater than zero. For example, scaffolding had the highest effect sizes when learning was assessed at the principles level, but effect sizes were statistically greater than zero and of substantial magnitude across the concept, principles, and application levels.

Results also help scaffolding researchers learn what scaffolding characteristics do not lead to differences in effect sizes—scaffolding customization, generic or context-specific nature of support, scaffolding function (e.g., conceptual and strategic), and whether scaffolding was designed to enhance content learning or higher-order skills.

The material covered in this book can be parlayed into stronger scaffolding designs. Further research should contribute to a greater understanding of the conditions under which and the strategies with which scaffolding leads to strong learning outcomes. Future research should also investigate how to extend scaffolding's reach to benefit underrepresented groups in STEM, a very important goal (Ceci, Williams, & Barnett, 2009; Syed, Azmitia, & Cooper, 2011; Thoman, Smith, Brown, Chase, & Lee, 2013). This could be pursued through a combination of strategies: look at the differences between scaffolds that work well among underrepresented groups, and those that are not as effective, examine the literature on designing effective instructional supports for members of underrepresented groups (Cuevas, Fiore, & Oser, 2002; Marra, Peterson, & Britsch, 2008), examine the literature on universal design for learning (Rao, Ok, & Bryant, 2014; Scott, Mcguire, & Shaw, 2003), and examine whether there are differences in how students from underrepresented groups are using scaffolds that could explain lower effectiveness (Belland & Drake, 2013).

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