

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).

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; Tzurriel, 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).

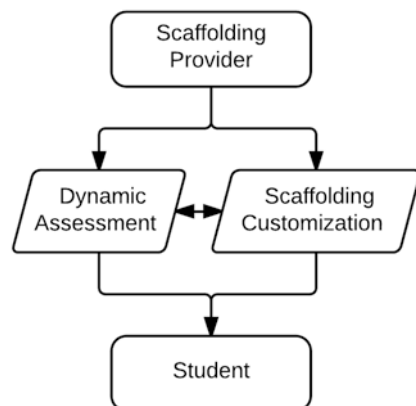
2.2 Scaffolding Elements

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 & Alevan, 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 & Alevan, 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 & Alevan, 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 & Alevan, 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 & Alevan, 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 & Alevan, 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-

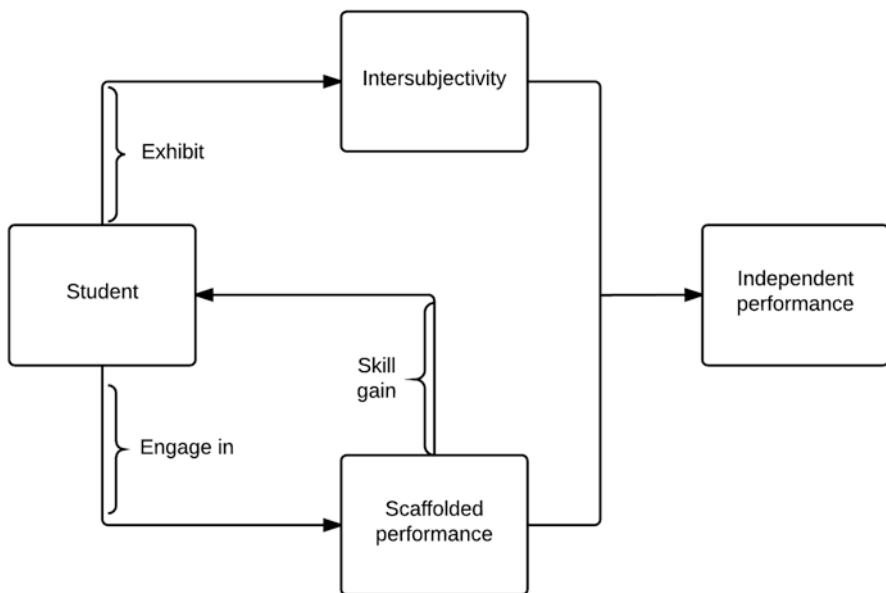


Fig. 2.2 Exhibiting intersubjectivity and engaging in scaffolded performance as predictors of the ability to engage in independent performance

comply with 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 (Van-Lehn, 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 & Hübsher, 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 post-modern 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 & Alevan, 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 & Alevan, 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). Stu-

dents 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, & Vandenhoven, 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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