2 Foundations of the Learning Sciences

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The learning sciences (LS) studies the design and implementation of effective learning environments, in addition to basic scientific research on learning (Kolodner, 1991). In this sense, LS embraces Stokes's (1997) notion of "use-inspired basic research." In its pursuits, LS research draws on a variety of theoretical perspectives on learning phenomena as they occur across a broad range of physical, social, and technological spaces. In this chapter, we describe the intellectual foundations that have influenced the learning sciences from its beginnings, and we identify the core elements of LS that unify the many chapters of this handbook.

Principles and Themes of the Learning Sciences

Bridging Research and Practice

Learning scientists work on the design and implementation of real-world educational systems – curricula, software, teaching practices, and social and interactional patterns – and also conduct basic scientific investigations. As a result of this joint focus, learning scientists are centrally concerned with bridging research and practice. This approach contrasts with the history of education research, where researchers and practitioners have long viewed each other with extreme skepticism and little trust. This focus on bridging research and practice distinguishes LS from related fields that are "basic sciences" – cognitive psychology, educational psychology, and anthropology – and those that are more "use inspired," such as instructional design and educational technology. An early example of a prototypical learning sciences project was the *Schools for Thought* classrooms implemented with funding from the James S. McDonnell Foundation throughout North America (Lamon et al., 1996). The innovations that were incorporated into *Schools for Thought* classrooms included: *Knowledge Forum* (science and rhetoric; see Scardamalia & Bereiter, Chapter 20, this volume), *The Adventures of Jasper Woodbury* (mathematics; Cognition and Technology Group at Vanderbilt, 1997), *Reciprocal Teaching* (reading; Palincsar & Brown, 1984), and *Fostering Communities of Learners* (classroom culture; Brown & Campione, 1994). *Schools for Thought* advanced our scientific understanding of the nature of classroom learning, teaching, and assessment in an intellectually, socially, and technologically dynamic learning environment. It also contributed substantially to the development and implementation of empirically based principles of learning environment design.

Scaling up: From Research Intervention to Widespread Implementation

The ideal progress of an LS project is to begin by developing an educational innovation, using an iterative design process that involves frequent evaluation in real-world settings; to then document the effectiveness of the innovation in a carefully observed test site – typically one classroom or one school with participating teachers who work closely with the research team; and then to *scale up* the innovation beyond the test site in order to broadly shape pedagogical practices, design principles, and education policies (Spillane, Reiser, & Reimer, 2002). Although scaling up effective interventions is critical for education reform, successful scale-up initiatives are rare (Penuel, Fishman, Cheng, & Sabelli, 2011). Members of the LS community, however, have been responsible for several successful scale-up efforts, including *Schools for Thought* (Lamon et al., 1996); *Cognitive Tutor Algebra* (Koedinger & Corbett, 2006); *Web-based inquiry science environment (WISE)* (Linn & Slotta, 2000); *Quest Atlantis* (Barab, Thomas, Dodge, Carteaux, & Tuzun, 2005); and *SimCalc* (Tatar et al., 2008); among others. These successful projects have provided valuable experience in taking research-based innovations and translating them into real-world practices that enhance student learning outcomes.

Scaling up has traditionally been defined in terms of the breadth of the dissemination and level of fidelity of an innovation (RAND, 2004). In contrast, contemporary evaluations of successful scale-up research tend to highlight the importance of tailoring the measures and practices to the specific implementation context (Dede, 2006; McDonald, Keesler, Kauffman, & Schneider, 2006). Recent evaluations suggest that effective reform must conform to the constraints of the local learning environments, and that practitioners must be recognized for the central role they play in carrying out fundamental change. Education scale-up researchers advocate forming collaborative relationships with teachers, school leaders, and designers in order to customize each implementation. Scale-up researchers strive to improve the implementation with each successive iteration of the design-implement-evaluate-redesign cycle.

Scientific and Engineering Approaches to the Study of Learning

The goal of basic research on the human mind – for example, a cognitive psychology perspective – is to produce reliable models and broad theories that describe, explain, and predict human behavior and development in ways that stand up to scrutiny by a community of scientific peers. Scientific theories advance our understanding of learning and pave the way for the design of new, effective innovations. This scientific ethos has dominated studies of human behavior, learning, education, workplace training, and human factors for more than a century (Cremin, 1961).

However, if the goal is to develop scalable educational innovations that transform schools and classrooms, scientific approaches have serious limitations, as follows. Scientific accounts of complex social phenomena are commonly based on the study of greatly simplified behaviors in methodologically favorable contexts (for example, the isolated individual studied in the psychological laboratory), which compromises their ecological validity and makes it difficult to scale up to a wide variety of authentic settings. Scientific theories are *descriptive* of learning and performance, but are rarely *prescriptive* of the instructional supports needed to foster that learning (Schwartz, Martin, & Nasir, 2005). Thus, scientific theories of learning "under-constrain" instructional design (Nathan, 1998), meaning that designers of learning environments must make many atheoretical decisions during planning and implementation.

LS is a *design science* drawn from an engineering ethos. In an engineering approach, success is seldom defined in terms of theoretical accounts of how the world operates, but by developing *satisficing* solutions for how things ought to be – innovations that *satisfy* existing conditions and *sufficiently* meet the stated goals within prevailing constraints (Simon, 1996). Efforts to design effective learning environments and activities cannot be based solely on scientifically validated theories of learning: theoretical advances are often too slow in coming, too blunt, and too idealistic. Engineering and other design-based approaches use faster methods of testing innovation. Design-based approaches (see Barab, Chapter 8, this volume) are goal directed and contextualized and often employ frequent, formative assessment (see Pellegrino, Chapter 12, this volume) as part of iterative design-implement-evaluate-redesign methods. This allows for highly responsive, evidence-based course corrections so that it is possible to realign solutions to suit local constraints and to resolve on-the-fly decisions that are underspecified by prevailing scientific models.

Influential Theories of Learning

Cognitive Science

Cognitive science is an interdisciplinary field, drawing primarily on cognitive psychology and computer science, which frames cognition as computation (Chalmers, 1993/2011). *Computation* is broadly defined to include the many classes of computational systems that computer scientists have developed and studied, from rule-based or algorithmic systems to connectionist or "massively parallel" systems. The goal of cognitive science is to develop an empirically based and computationally verifiable (i.e., programmable) theory of cognition

(Newell & Simon, 1976). The mental processes and structures that cognitive scientists study most often are attention, perception, semantic and episodic memory, language development and use, concepts and categorization, reasoning and decision making, problem solving, procedural and conceptual learning, and consciousness. Many cognitive scientists hold to the principle of computational equivalence, also known as *multiple realizability*: a cognitive system can achieve the same output (e.g., a behavior) for a specific set of inputs (e.g., words and images on a screen) using vastly different "realizing" lower-level substrates of algorithms, representations, and material substrates (e.g., the silicon chips of computers or the neurons of the human brain).

Situated Cognition

Situated cognition is heavily influenced by phenomenological philosophy and its central insight that we know and make sense of the world through direct perception of the actionable possibilities of our interactions with our environment (Gibson, 1977). Phenomenologists argue that perception and representation exist as grounded interaction *with* the world, rather than as internal mental representations *about* the world (Dreyfus, 2002). Phenomenologists focus on the contextualized activity of complex organizations of people, technology and information resources, and the physical environment (Greeno, 1997). Thus, phenomenology places agency and action in the world, rather than internal mental processing, at its core (Anderson, 2003; Larkin, Eatough, & Osborn, 2011). Situated cognition rejects models of cognition that are based primarily on computational processes and structures composed of symbol systems that are abstract, amodal, and arbitrarily mapped to the world.

The situated cognition perspective holds that cognitive behavior is embodied, embedded, and extended. An *embodied cognition* approach (Abrahamson & Lindgren, Chapter 18, this volume; Nathan, 2014) is valuable when body states and body-based resources are inextricably tied to intellectual behavior (Glenberg, 1997). *Embedded cognition* (closely related to *distributed cognition*) holds that cognition is mediated by the physical and social environment of the individual in cases where the environment is used to off-load task demands that might otherwise be performed mentally. An influential example of distributed cognition was Hutchins's (1995) study of the emergence of navigation as the work of a team interacting with instruments and tools, maps, and the space the team inhabits. Theories of *extended cognition* go further, arguing that in some cases the social and physical environment, along with the individuals in it, jointly *constitute* the cognitive system (Clark & Chalmers, 1998).

Constructivism

Constructivism posits that learning involves the active creation of mental structures, rather than the passive internalization of information acquired from others or from the environment. Jean Piaget, the originator of constructivism, argued that all learning was mediated by the construction of mental objects that he called *schemas*, which were essentially Kantian a priori categories (e.g., space, time, causality). Piaget's original articulation focused on how schemas emerge from the interaction and experimentation of the child with the physical world. For Piaget, schemas first emerge as concrete actions and gradually develop into more abstract and conceptual mental entities.

Constructivism has been broadly influential in education and forms one of the core elements of learning sciences approaches. Some learning scientists have also been influenced by variants of constructivism. For example, *radical constructivists* (e.g., von Glasersfeld, 1989) hold that because we each form our own realities there can be no external truth. *Social constructivists* (e.g., Mead, Vygotsky) posit that the knowledge construction process is inherently mediated by social interaction, including the use of language.

The emergence of the San Francisco Exploratorium and other interactive science centers (see Crowley, Pierroux, & Knutson, Chapter 23, this volume) was directly inspired by the dissemination of Piagetian ideas in America in the 1960s (Flavell, 1963). One of the seminal contributions of constructivism to education was the development of the Logo programming language by Seymour Papert (1980), soon after he returned from studying with Piaget in Geneva. Logo enables children to construct notions of geometry and computation through the exploration of space and the control of actions as mediated through programming of an animated "turtle." Constructivism also figured prominently in the "Great Debate" on reading (whole language versus phonics), and the "Math Wars" (back to basics versus constructivist approaches), and remains influential in educational reform and the emergence of a convergent set of curriculum and instructional standards in primary and secondary education content areas.

Sociocultural Theory

By the 1980s, after the burst of activity associated with 1970s artificial intelligence (AI) and cognitive science, many of these scholars had begun to realize that their goal – to understand and simulate human intelligence in the computer – was still very far off. The 1980s disillusionment with AI was so severe that it was informally known as "the AI winter." Researchers began to step back and think about why the cognitive sciences had not been more successful. The most influential answer was provided by a group of interrelated approaches, including the sociocultural, situative, and distributed cognition approaches (Greeno & Engeström, Chapter 7, this volume; Salomon, 1993). Socioculturalists began with the observation that all intelligent behavior was realized in a complex environment – a human-created environment filled with tools and machines, but also a deeply social environment with collaborators and partners.

Some of the most interesting work along these lines focused on informal learning in non-Western societies without formal schooling (Cole, 1996; Lave, 1988; Rogoff, 1990; Saxe, 1991). Equally influential studies examined the socially distributed nature of knowledge work – including studies of navy ship navigation (Hutchins, 1995), of London Underground control rooms (Heath & Luff, 1991), of office systems (Suchman, 1987), and of air traffic control centers (Hughes, Shapiro, Sharrock, Anderson, & Gibbons, 1988). This research revealed that, outside of formal schooling, almost all learning occurs in a complex social environment and that learning is hard to understand if one thinks of it as a mental process occurring within the head of an isolated learner.

Sociocultural scholars draw on the classic theories of Russian psychologist Lev Vygotsky (1978), who argued that social interaction was the primary driver of intellectual development. He contended that thought emerged during development as social interaction gradually became internalized. Through mechanisms like scaffolding (see Reiser & Tabak, Chapter 3, this volume), children could perform at a higher level than when operating alone, and these opportunities could accelerate intellectual development.

The sociocultural approach has been widely influential in all of the disciplines participating in the learning sciences.

- Artificial intelligence researchers began to emphasize distributed cognition in part because of the rapidly evolving network technologies of the 1980s and 1990s.
- Cognitive psychology researchers began to study teamwork, collaboration, group dynamics, and the role of social context in cognitive development.
- Education researchers began to study classroom collaboration, collaborative discourse in student groups, and project teams.

Learning scientists use these approaches in particular to explain *informal learning* (Crowley et al., Chapter 23, this volume) – learning outside of schools, whether at home with the family, on the playground with peers, or in apprenticeship settings where youth learn a trade or other culturally valued skills (Lave & Wenger, 1991; also see Collins and Kapur, Chapter 6, this volume).

American Pragmatism

Pragmatist John Dewey developed *child centered pedagogy*, where the child's interest and experience drove the learning environment design. Dewey's theories emphasized the importance of *inquiry* – that children learn best when they interact with the world much as a scientist or philosopher does, by posing hypotheses and testing them against reality and reason. There are close parallels with Piaget's theory; Piaget and Dewey were contemporaries and both were widely influential through much of the 20th century.

George Herbert Mead, another pragmatist working during the first half of the 20th century, argued that thought is *emergent* from the organism's interaction with reality, and that communication and language begin as concrete and simple gestures and gradually become more abstract (again, note the close parallels with Piaget). Blumer, a student of Mead's, developed *symbolic interactionism*, which focused on the close analysis of how people exchange symbols – whether verbal symbols (words) or gestures and body language. During the 1960s and 1970s, Blumer's ideas were further developed by Garfinkel's *ethnomethodology*, which holds that the best way to understand social phenomena is to ask participants what they are doing and how they are interpreting it. A variant of ethnomethodology, *conversation analysis*, likewise proposes that the best way to analyze the social context of an encounter is to closely examine how participants talk about that social context and convey its relevance to them. These approaches remain influential in LS, particularly among researchers who use qualitative and ethnographic methods to study videotapes of naturally occurring learning encounters (see Goldman, Zahn, & Derry, Chapter 11, this volume).

The Scope of Learning Behaviors

Time Scales of Learning

LS studies learning across levels of space, time, and scale. Figure 2.1 (adapted from Nathan & Alibali, 2010) reflects one way to visualize the unified nature of learning phenomena as they emerge through variation of only a single parameter: time (Newell, 1990). From an individualist psychological perspective, what unifies all learning phenomena is a set of shared mental *processes*. In contrast, LS holds that what unites learning phenomena is that learning occurs in the context of *designed learning environments* – classrooms, the home, workplaces, museums, even the psychology laboratory. In each case, the learning environment is an artifact designed in a historical context, in

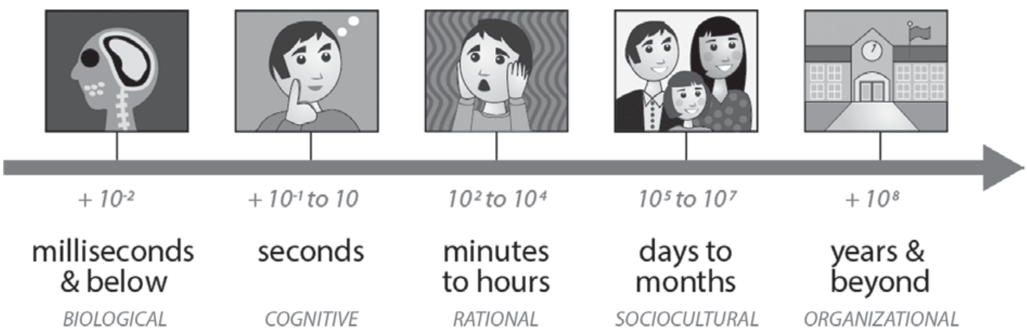

Figure 2.1. *Log_{10} time scale of human learning. Adapted from Nathan and Alibali (2010).*

response to cultural constraints and expectations, which is intended to bring about societally desirable learning outcomes.

Elemental Research

To investigate the range of learning phenomena within LS more fully, in addition to a time scale analysis, Nathan and Alibali (2010) drew a distinction between *systemic* and *elemental* approaches to learning research. *Elemental* approaches are so called because they focus on the component elements of a complex learning environment – and as such, they rely on the *factoring assumption*: they assume that the many components of the system (such as context) can be "factored out" and analyzed independently (Greeno & Engeström, Chapter 7, this volume). *Systemic* approaches reject the factoring assumption. Thus, they analyze learning at the level of the entire complex system.

Elemental approaches include research performed using correlational and experimental methods, structural equation modeling and factor analysis, and computer modeling approaches. While much cognitive psychology research is elemental in nature, some of it – for example, research from a situated cognition perspective – can be systemic. Thus, it would be erroneous to assign all quantitative methods or all methods that lie in the lower time bands of Figure 2.1 to elemental approaches. Methods that draw on learning analytics, such as educational data mining (Baker & Siemens, Chapter 13, this volume) and whole-brain methods in cognitive neuroscience, for example, contradict this pattern. Similarly, though a great deal of qualitative research aligns with systemic approaches, some, such as think aloud reports, are used to factor out elemental processes from task and environmental influences.

Levels of Analysis

Scientists study complex systems at different *levels of analysis*: some phenomena are better studied by analyzing the complete system (the "higher" level of analysis), and other phenomena are better studied by reductively analyzing the system in terms of its component elements ("lower" levels of analysis). Learning environments are complex social and technological systems, and approaches that analyze them in terms of the psychological characteristics of the participating individuals are "lower level" and often are referred to as *methodologically individualist* or *reductionist*.

Descriptions of phenomena at higher levels of analysis are necessarily consistent with descriptions of the same systems at lower levels of analysis. This is because all such systems are characterized by *supervenience*: properties and entities at the higher level of analysis are *realized* or *instantiated* in lower-level component properties and processes. Technically, *supervenience* refers to a system where any change in the higher-level description must

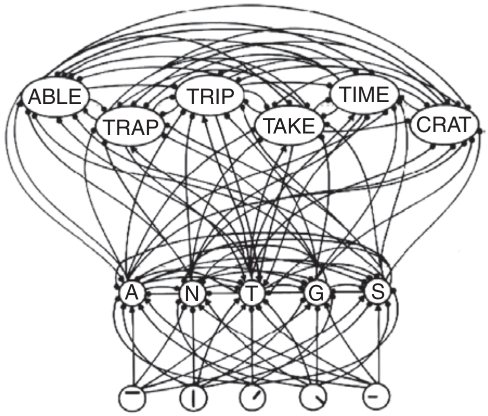

Figure 2.2. *An example of supervenience: Pen strokes combine to form letters; letters combine to form words. Copied from McClelland and Rumelhart (1986).*

necessarily result in a corresponding change in the lower-level description (Sawyer, 2005).

Figure 2.2 provides an illustrative example of a simple system of supervenience, where individual pen strokes (bottom of the figure) are combined in conventional ways to form letters, and letters combine to form words. Words are the "higher level" and they supervene on letters, while letters supervene on strokes.

Systemic Research

In the history of science, elemental reductionist approaches have had great success. This had led some education researchers to suggest that lower-level analysis (for example, psychological studies of individual learners) is the most promising approach for education research. LS research, in contrast, is distinguished by its regard for both elemental and systemic research, with the approach determined by the nature of the phenomenon.

In complex systems, higher levels always supervene on lower levels. And yet, in some complex systems, higher levels can exhibit emergent properties that are difficult to analyze and explain in elemental terms. Systemic approaches assume that context and behavior cannot be "factored out"; these approaches include situated cognition and cultural-historical activity theory (CHAT), social learning theory (Miyake & Kirschner, Chapter 21, this volume), and ethnomethodological methods. These approaches all choose a system-level unit of analysis, maintaining that this better preserves the essential qualities of the learning environment than does analyzing the phenomenon by reducing it to a set of factorable elements (Leont'ev, 1981; Wertsch, 1985).

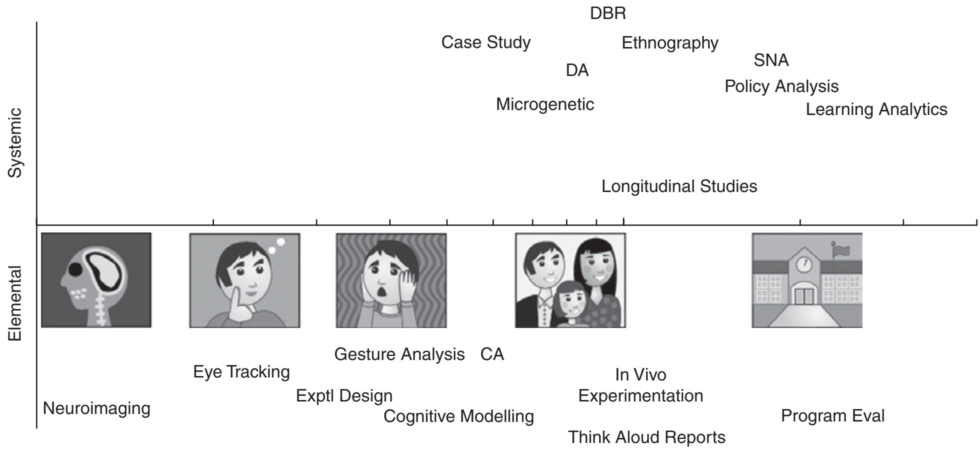

Figure 2.3. *Systemic (above) and elemental (below) research plotted on a logarithmic time scale.*

Learning Sciences as a Design Science

As a field, LS draws on research from both elemental and systemic perspectives when developing, implementing, and evaluating effective learning environment designs for behaviors observed at various time scales (Figure 2.3). In this section, we review some of the key findings from these two research perspectives, and offer guidance for how elemental and systemic perspectives can be productively combined to achieve the broad aims of LS: to advance our basic understanding of learning while applying that understanding to the design of real-world learning environments.

Elemental View: Evidence-Based Principles of Learning and Design

The core findings that have emerged from several decades of elemental learning research have been summarized in several review articles (Dunlosky, Rawson, Marsh, Nathan, & Willingham, 2013; Graesser, Halpern, & Hakel, 2008; Pashler et al., 2007). These reviews converge on a small number of overarching principles for facilitating learning: the importance of repetition and practice; managing the demands on cognitive and attentional resources; engaging the learner in the active construction of meaning and knowledge; and metacognitive awareness. This body of research suggests the following design guidelines for how to develop effective learning environments.

Strategically Regulated Repetition and Practice

Learning benefits immensely from strategically regulated repetition and practice, especially when it is accompanied by reliable and timely feedback.

Performance is generally superior when repetition and practice are spaced apart in time. The feedback practice testing provides is valuable, in part because it emulates the assessment experience that is to come, and the necessary *retrieval practice* – the generation of responses by retrieving information from memory. For certain kinds of test performance, such as rapid and accurate performance of a narrow set of perceptual or motor skills, practice that is *blocked* – continuous repetition of the same behavior, rather than mixing practice of differing behaviors – is most beneficial. In more conceptually oriented testing, it is more beneficial to *interleave* practice by mixing multiple types of tasks. The benefit is thought to result because interleaving provides learners with the opportunity to practice item discrimination as well as strategy selection.

Managing Cognitive Demands while Integrating across Information Sources

Exposure to and integration across varied sources of information is key to many forms of learning. Often, we recall things more reliably and for longer periods of time when they are presented in complementary modalities – such as when people combine verbal associations with mental imagery.

Although people can remember an enormous amount of information over a lifetime, cognition is mediated by a much smaller capacity "working memory" system that attends to and encodes information. These limitations are further restricted when there are substantial, real-time demands – sometimes referred to as *cognitive load* – such as making decisions based on rapidly changing events. Learning environments can reduce cognitive load, and thus enhance learning, by minimizing split attention across sources of information, or reducing the demands to connect and combine conceptual relations across different modalities. Cognitive load can also be reduced with well-structured learning materials, with experiences that are organized and coherent, and by segmenting complex information into manageable parts. Cognitive load can also be reduced by presenting material in the form of stories and case studies, because these genres provide organization by using familiar narrative forms.

Engaging the Learner in the Active Construction of Meaning and Knowledge

Learning is more effective when learners are actively engaged in the construction of meaning and knowledge. If cognitive load is reduced too much – if material is too organized and task demands are too easy – then people will process the information passively and shallowly, with little learning occurring (e.g., McNamara, Kintsch, Songer, & Kintsch, 1996).

Learning is more effective when learners are encouraged to ground new experiences and concepts in perceptual and motor experiences, language, and prior knowledge. Activities that tend to ground meaning, and thus result in more effective knowledge construction, include practice testing, asking and answering deep questions, participating in dialog and argumentation that requires one to articulate one's position and explain one's reasoning (see Andriessen & Baker, Chapter 22, this volume), and participating in project-based collaboration (see Krajcik & Shin, Chapter 14, this volume). It can also be productive to encounter desirable difficulties, and even to engage in failure, because this activates relevant prior knowledge, varies the learning experiences, elicits explanations, distributes practice, and targets knowledge gaps for repair (see Collins & Kapur, Chapter 6, this volume).

Active construction of meaning is particularly important in making sense of abstract formalisms such as formulas and diagrams. Formalisms support analogical mapping, generalization, and the flexible transfer of knowledge to new domains. Yet they are steeped in technical and arbitrary systems of notation, which separate them from the real-world contexts to which they apply. Grounding formalisms in concrete and familiar ideas and experiences through methods such as *progressive formalization* supports meaningful interpretation of these abstract representations and improves learners' abilities to access and apply them when it is relevant and efficient to do so (Nathan, 2012).

Metacognitive Awareness

Metacognition (Winne & Azevedo, Chapter 4, this volume), including the ability to monitor one's level of understanding and reflect on what and how one learns, is a cornerstone of human cognition. Its value is evident whenever learners pause to evaluate their progress and use the outcome of that evaluation to direct their own reasoning process or to restructure their learning environment. Yet most learners need help doing effective monitoring and self-regulation, and they require feedback to verify their self-evaluations. For example, students make many poor choices about study methods and can be wildly inaccurate at predicting their effectiveness (Dunlosky et al., 2013). With proper support, however, students can develop good monitoring and self-regulation skills and can improve their efficiency, retention, and self-monitoring.

Systemic View: Evidence-Based Principles of Learning and Design

Systemic research asserts that it is not possible to analytically separate participants' actions from one another or from the learning environment. From this perspective, context cannot be treated as a container in which isolated elemental "regularities" occur; it is an integral part of the complex causal field that gives rise to the phenomenon under study. Lave powerfully illustrated this point when she stated that everyday cognition is "*stretched over, not divided among* – mind, body, activity and culturally organized settings" (1988, p. 1; emphasis added).

Methods of Systemic Research

Systemic research aims to document the situated learning practices and resources people use in learning environments – including classrooms, but also workplace settings, museums, and their everyday lives as members of their communities – to establish social order and make sense of their world. Systemic research methods include microgenetic analysis (Chinn & Sherin, Chapter 9, this volume), conversation analysis, interaction analysis, and ethnomethodology. Interaction analysis methodology has been particularly influential within the LS community (Enyedy & Stevens, Chapter 10, this volume), and views learning as "a distributed, ongoing social process, in which evidence that learning is occurring or has occurred must be found in understanding the ways in which people collaboratively do learning and do recognize learning as having occurred" (Jordan & Henderson, 1995, p. 42).

Design-based research (DBR; Barab, Chapter 8, this volume) is another systemic methodology that documents learning interactions, mechanisms of change, and the influences that bring about these changes (Brown, 1992; Cobb, Confrey, Lehrer, & Schauble, 2003; Collins, Joseph, & Bielaczyc, 2004; Design-Based Research Collective, 2003; Hawkins, 1997). Consistent with the design sciences, DBR is not primarily concerned with describing existing behaviors, but with designing learning environments to foster maximally effective behaviors (Barab & Squire, 2004; Simon, 1996). A variant of DBR has formed around policy and implementation research (Penuel & Spillane, Chapter 32, this volume). Thus, DBR blurs traditional distinctions between research and development, contributing to both.

Summary Findings from Systemic Research

Systemic approaches analyze learning in holistic terms, as a complex system phenomenon. Learning environment designs that are influenced by systemic research focus on the level of the group, or the sociotechnical learning environment. For example, they might address the nature of interpersonal interactions in the service of meeting social, participatory, and identity-related goals. Many prominent LS-inspired curricular designs are grounded in systemic research, including problem-based learning (Lu, Bridges, & Hmelo-Silver, Chapter 15, this volume), project-based learning (Krajcik & Shin, Chapter 14, this volume), and inquiry-based learning. Findings from systemic research can be organized into three general areas: support for collaboration and argumentation; engaging learners in disciplinary practices; and providing appropriate levels of support for guided inquiry and project-based learning.

Collaborative Discourse and Argumentation

Conversation mediates between group participation and individual learning. Members of cooperative groups exhibit greater learning gains than those in competitive or individualistically structured learning environments (Cohen, 1994). Furthermore, the quality of the collaborative discourse influences subsequent transfer performance by individual students (Barron, 2003). *Computer-supported collaborative learning* (CSCL; Stahl, Koschmann, & Suthers, Chapter 24, this volume) fosters intersubjective meaning making through shared representations and task structure.

There are several potential explanations for how collaboration and argumentation improve individual participants' learning. For example, learning is enhanced when people generate and listen to explanations. Participants must generate precisely formulated statements and questions to argue effectively (Andriessen & Baker, Chapter 22, this volume). Interlocutors must make their knowledge explicit, which fosters new connections. Collaboration can reveal knowledge gaps and misconceptions that may be repaired. Argumentation invites speakers to reflect on their reasoning processes, which can promote conceptual change (diSessa, Chapter 5, this volume). Co-elaboration and co-construction of ideas and representations can influence subsequent, ongoing interaction (Cobb et al., 1997).

Unfortunately, learners do not spontaneously collaborate effectively (Azmitia, 1996). Students often need modeling, guidance, or direct instruction and scripts to develop and apply collaboration skills, such as turn taking, active listening, critical evaluation, and respecting others' opinions (Krajcik, Czerniak, & Berger, 2002).

Engaging in Accessible Forms of Authentic Disciplinary Practices

Research shows that active engagement in authentic disciplinary practices results in enhanced learning outcomes – such as those promoted by programs like *The Adventures of Jasper Woodbury* (Cognition and Technology Group at Vanderbilt, 1997), *Fostering Community of Learners* (Brown & Campione, 1994), and *Kids as Global Scientists* (Songer, 1996). Engaging learners in authentic practices is effective for several reasons (Edelson, 2006). Disciplinary practices provide a meaningful context that *anchors* students' emerging understanding to authentic contexts and legitimate practices. They provide coherence to new practices and information, and orient learners toward future application of their learning. Disciplinary practices can increase student motivation. Authentic disciplinary practices also assist students in understanding the *epistemology* of a discipline – the ways knowledge in a field is structured and produced.

Just as with collaboration and argumentation, learners do not naturally know how to engage in authentic practices. Care must be taken to structure the learning environment and activities in ways that are accessible and that follow a developmental progression. Skillful pedagogical practices are necessary to encourage and support students' development, and then, just as skillfully, foster their autonomy. Technological tools can be designed to present phenomena (e.g., weather system data) that are accessible, engaging, and yet not overwhelming to students (Songer & Kali, Chapter 28, this volume).

Exploiting the distributed nature of cognition in these sociotechnical learning environments helps individuals manage the potentially high cognitive load (Edelson, 2006). Outside experts can help students navigate some of the complexities. Pedagogical approaches, such as cognitive apprenticeship, organize the use of methods such as modeling, coaching, scaffolding, and fading to facilitate development of both conceptual and procedural skills through guided participation. Learning environments need to make explicit the "tacit knowledge" underlying the professional practices of experts – the deeply ingrained expertise that they have automatized and no longer have conscious access to.

Guided Inquiry and Project-Based Learning

Guided inquiry results in more effective learning than unguided discovery learning or than simply hearing the information to be learned (Furtak, Seidel, Iverson, & Briggs, 2012; Hmelo-Silver, Duncan, & Chinn, 2007). Guided inquiry is effective because it elicits many of the most effective learning mechanisms discussed earlier, all in one coherent system. Students repeatedly generate and articulate their knowledge, ask deep questions, self-explain, and justify their reasoning. Inquiry experiences frequently incorporate repeated testing.

Like guided inquiry, project-based learning (PBL; Krajcik & Shin, Chapter 14, this volume) allows students to learn by doing, explaining, and applying ideas to solve meaningful problems. Students in PBL classrooms show better test performance than students in lecture and demonstration classrooms, regardless of gender or ethnicity (Marx et al., 2004). As Graesser and colleagues (2008) noted, students are unlikely to spontaneously take up inquiry, disciplinary, and project-based practices, and they need substantial assistance or "scaffolding" to discover key principles, connect prior knowledge, and employ effective learning and monitoring strategies (Reiser & Tabak, Chapter 3, this volume).

Rethinking Scale-up: Integrating Systemic and Elemental Views

Scale-up is a central aim for LS research. The systemic perspective addresses the important interrelationships between a design innovation and its context and use. However, it is difficult to manage the complexity of systems (Wilensky & Jacobson, Chapter 16, this volume), and attempts to control them can lead to unintended consequences. Elemental approaches bring powerful methods for precision and control that enable the research design team to establish causal relations that inform scale-up efforts. But the reductionism of elemental approaches is insensitive to local constraints and seldom scales up (Dede, 2006). Bridging systemic and elemental perspectives would result in more efficient means of developing effective learning innovations, with designs that bridge research and practice.

As an alternative to traditional scale-up approaches, Nathan and Alibali (2010) proposed the *scale-down method* as one way of integrating systemic and elemental approaches. The scale-down method begins by studying a system from a systemic perspective – by examining the learning environment in the complex settings in which it naturally occurs (e.g., a classroom). Then, analysis of these systemic observations is used to develop hypotheses for how to improve system performance, first by identifying potential subsystems within *nearly decomposable systems* that impact system performance; second, by modifying the design and performance of these subsystems; third, by reintegrating modified subsystems into the system; and finally, by observing behavior of the system as a whole in its natural context.

Fully decomposable systems are relatively simple systems made up of modules that function independently. In contrast, *nearly* decomposable systems are marked by components of a system, where "the short-run behavior of each of the component subsystems is approximately independent of the short-run behavior of the other components," though "in the long run, the behavior of any one of the components depends in only an aggregate way on the behavior of the other components" (Simon, 1962, p. 474). Thus, interactions in nearly decomposable systems are relatively strong within subsystems, while interactions between the subsystem and the rest of the system are relatively weak, although they cannot be ignored. For example, saccades, which direct eye movement, are fully decomposable from many other aspects of visual tasks, while reading comprehension strategies are nearly decomposable, in that they can be measured and improved in relative isolation, but ultimately interact with the environment and task goals (Perfetti, 1989).

The aim of scale-down is to improve systemic performance by improving, when possible, the design of subsystems – whether curricular materials, interaction patterns, or teacher behaviors. Refinement of the design and performance of a subsystem can draw on the precision and control that characterize elemental methods, as well as systemic methods of investigation and design. In this way, refinement of a nearly decomposable system is performed in a recursive manner, alternately using elemental and systemic methods when necessary. The development of measurement instruments used in service of systemic research, for example, relies on near decomposability, in that one needs to develop a means of extracting one aspect of the system's behavior and subjecting it to an analytic framework that supports categorization or quantification.

Engineering efforts use near decomposability when designing, evaluating, and improving complex technological and social systems. One method used historically in engineering is *functional decomposition* (Bradshaw, 1992). Functional decomposition allows designers to optimize performance of a nearly decomposable subsystem, such as a wing design for an airplane, using elemental methods (measurements of lift) as well as systemic methods (observing behavior in the context of a wind tunnel) to improve the overall performance of the system. Functional decomposition is efficient because it is cheaper and easier to test and modify the design of subsystems of a complex system than to redesign the system as a whole.

Because the behaviors and aims of people differ radically from those of designed technological systems, education may not directly lend itself to functional decomposition methods, per se. But learning environment design may nonetheless draw some inspiration from techniques like functional decomposition. Laboratory experimentation offers one set of elemental methods used to support scale-down. Computer-based learning companions, pedagogical agents, and simulated students also offer ways to isolate and improve complex collaboration and pedagogical interactions (Biswas, Leelawong, Schwartz, & Vye, 2005; Dillenbourg & Self, 1992; Ur & VanLehn, 1995). *Standardized students* and *standardized parents* – drawing on *standardized patient* work in medical training and assessment – have live actors in authentic settings who provide personable interactions for teacher training and assessment (Dotger, 2010), which can enhance the overall learning environment design.

The problem with using elemental methods exclusively to analyze complex systems is that the factoring assumption neglects the inherent interactions of the specific participants and local context with the functioning of the component elements once they are reintroduced into the system. The scale-down method emphasizes the important role of the *reintegration process*. Redesigned subsystems must be thoughtfully reintegrated by practitioners familiar with the elemental qualities of interest as well as with the particulars of the larger system, and then studied in real-world learning environments using systemic methods.

New programs of research are emerging that are consistent with the scale-down method, especially in mathematics education. Davenport (2013) reported on the carefully coordinated use of experimental methods, learning analytics, and eye tracking for the redesign of a widely used middle school mathematics curriculum, *Connected Mathematics 2*. The organization and content of the words and images in the printed booklets, the practice schedule for gaining mastery of concepts and skills, the testing practices, the use of worked examples and self-explanation for homework activities, and teacher professional development are treated as nearly decomposable subsystems, which a team of specialists observed, modified, and then reintegrated for classroom implementation as a systemic whole. In a second example, Lehrer, Kim, Ayers, and Wilson (in press) used a series of design experiments to support middle school students' statistical reasoning. Although the emphasis was the formation of a system within which students showed development along a hypothesized learning progression, nearly decomposable components were identified to structure performance measures and staff development. Teachers with experience from prior design work led aspects of the system implementation and integration of components.

Scale-down is one way to productively address tensions between systemic and elemental approaches (Anderson, Reder, & Simon, 2000). Much of LS research and development foregrounds the systemic perspective, with primary attention to the complex interactions and authentic practices as they occur in ecologically valid settings. Elemental approaches then serve a subordinate though complementary role by aiding in the control, analysis, and redesign of subsystems. By strategically combining elemental and systemic approaches, scale-down enhances design, development, and implementation of promising educational innovations, while contributing to the efficient advancement of empirically based theories of learning.

Conclusions

The learning sciences is an interdisciplinary field that emerged from a historical intersection of multiple disciplines focused on learning and learning environment design. Consequently, learning sciences blends research and practice – and views the two approaches as synergistic. For example, observing what happens when a new learning environment is implemented often results in new foundational understandings about mechanisms of learning and new design principles.

The theoretical foundations of LS include a broad range of social scientific theories. Some of these theories – such as cognitivism and constructionism – focus on learning at the level of the individual. These theories are generally associated with elemental research methodologies. Other theories are used to better understand embedded and situated learning – how learning is influenced by, and in some cases inextricably interwoven with, social and cultural context. These theories are generally associated with systemic research methodologies.

The chapters of this handbook share the two core defining features of LS research: they bridge research and practice, and they combine elemental and systemic perspectives on learning across a range of scales. We believe such research has great potential to enhance our scientific understanding of learning, while at the same time resulting in innovative and effective learning environment designs that foster enhanced learning outcomes.

References

Anderson, J. R., Reder, L. M., & Simon, H. A. (1996). Situated learning and education. *Educational Researcher*, 25(4), 5–11.

Anderson, M. L. (2003). Embodied cognition: A field guide. *Artificial Intelligence*, 149, 91–130.

Azmitia, M. (1996). Peer interactive minds: Developmental, theoretical, and methodological issues. In P. B. Baltes & U. M. Staudinger (Eds.), *Interactive minds:*

Life-span perspectives on the social foundation of cognition (pp. 133–162). New York: Cambridge University Press.

Barab, S., & Squire, K. (2004). Design-based research: Putting a stake in the ground. *The Journal of the Learning Sciences*, 13(1), 1–14.

Barab, S., Thomas, M., Dodge, T., Carteaux, R., & Tuzun, H. (2005). Making learning fun: Quest Atlantis, a game without guns. *Educational Technology Research and Development*, 53(1), 86–107.

Barron, B. (2003). When smart groups fail. *The Journal of the Learning Sciences, 12*, 307–359.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, 59, 617–645.

Biswas, G., Leelawong, K., Schwartz, D., Vye, N., & The Teachable Agents Group at Vanderbilt. (2005). Learning by teaching: A new agent paradigm for educational software. *Applied Artificial Intelligence*, 19(3–4), 363–392.

Bradshaw, G. F. (1992). The airplane and the logic of invention. In R. N. Giere (Ed.), *Cognitive models of science* (pp. 239–250). Minneapolis: University of Minnesota Press.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *The Journal of the Learning Sciences*, 2(2), 141–178.

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

Chalmers, D. J. (1993/2011). A computational foundation for the study of cognition. *Journal of Cognitive Science*, 12(4), 323–357.

Clark, A., & Chalmers, D. (1998). The extended mind. *Analysis*, 58(1), 7–19.

Cobb, P., Gravemeijer, K., Yackel, E., McClain, K., & Whitenack, J. (1997). Mathematizing and symbolizing: The emergence of chains of signification in one first-grade classroom. In D. Kirshner & J. A. Whitson (Eds.), *Situated cognition: Social, semiotic, and psychological perspectives* (pp. 151–233). Mahwah, NJ: Lawrence Erlbaum Associates.

Cobb, P., Confrey, J., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher*, 32(1), 9–13.

Cognition and Technology Group at Vanderbilt. (1997). *The Jasper Project: Lessons in curriculum, instruction, assessment, and professional development*. Mahwah, NJ: Lawrence Erlbaum Associates.

Cohen, E. G. (1994). Restructuring the classroom: Conditions for productive small groups. *Review of Educational Research*, 64(1), 1–35.

Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *The Journal of the Learning Sciences*, 13(1), 15–42.

Cremin, L. A. (1961). *The transformation of the school: Progressivism in American education, 1876–1957* (vol. 519). New York: Knopf.

Davenport, J. (2013). Reciprocal relations between research and practice: How improving curricular materials led to new research questions. Paper presentation to the Annual Meeting of the American Educational Research Association (San Francisco).

Dede, C. (2006). Evolving innovations beyond ideal settings to challenging contexts of practice. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 551–566). New York: Cambridge University Press.

Design-Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher*, 32(1), 5–8.

Dillenbourg, P., & Self, J. (1992). People power: A human-computer collaborative learning system. In C. Frasson, G. Gauthier, & G. McCalla (Eds.), The 2nd International Conference of Intelligent Tutoring Systems, Lecture Notes in Computer Science, 608, Springer-Verlag, 651–660.

Dotger, B. H. (2010). "I had no idea": Developing dispositional awareness and sensitivity through a cross-professional pedagogy. *Teaching and Teacher Education*, 26(4), 805–812.

Dreyfus, H. L. (2002). Intelligence without representation – Merleau-Ponty's critique of mental representation: The relevance of phenomenology to scientific explanation. *Phenomenology and the Cognitive Sciences*, 1(4), 367–383.

Dunlosky, J., Rawson, K. A., Marsh, E. J., Nathan, M. J., & Willingham, D. T. (2013). Improving students' learning with effective learning techniques: Promising directions from cognitive and educational psychology. *Psychological Science in the Public Interest*, 14(1), 4–58.

Edelson, D. C., & Reiser, B. J. (2006). Making authentic practices accessible to learners: Design challenges and strategies. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 335–354). New York: Cambridge University Press.

Flavell, J. H. (1963). *The developmental psychology of Jean Piaget* (vol. 1). Princeton, NJ: Van Nostrand.

Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. *Review of Educational Research*, 82(3), 300–329.

Garfinkel, H. (1967). *Studies in ethnomethodology*. Englewood Cliffs, NJ: Prentice Hall.

Gibson, J. J. (1977). The concept of affordances. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting, and knowing: Toward an ecological psychology* (pp. 67–82). Hillsdale, NJ: Lawrence Erlbaum Associates.

Glenberg, A. M. (1997). What memory is for: Creating meaning in the service of action. *Behavioral and brain sciences*, 20(01), 41–50.

Graesser, A. C., Halpern, D. F., & Hakel, M. (2008). 25 principles of learning. Washington, DC: Task Force on Lifelong Learning at Work and at Home. Retrieved December 8, 2008, from http://www.psyc.memphis.edu/learning/whatweknow/index.shtml.

Greeno, J. G. (1997). On claims that answer the wrong questions. *Educational Researcher*, 26(1), 5–17.

Hawkins, J. (1997). *The National Design Experiments Consortium: Final Report*. New York: Center for Children and Technology, Educational Development Center.

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist*, 42(2), 99–107.

Hutchins, E. (1995). *Cognition in the wild*. Cambridge, MA: MIT Press.

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *The Journal of the Learning Sciences*, 4(1), 39–103.

Koedinger, K. R., & Corbett, A. T. (2006). Cognitive tutors: Technology bringing learning science to the classroom. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences*. New York: Cambridge University Press.

Kolodner, J. L. (1991). The Journal of the Learning Sciences: Effecting changes in education. *Journal of the Learning Sciences*, 1, 1–6.

Krajcik, J., Czerniak, C., & Berger, C. (2002). *Teaching science in elementary and middle school classrooms: A project-based approach* (2nd ed.). Boston, MA: McGraw-Hill.

Lamon, M., Secules, T., Petrosino, A. J., Hackett, R., Bransford, J. D., & Goldman S. R. (1996). Schools for thought: Overview of the project and lessons learned from one of the sites. In L. Schauble & R. Glaser (Eds.), *Innovation in learning: New environments for education* (pp. 243–288). Mahwah, NJ: Lawrence Erlbaum Associates.

Larkin, M., Eatough, V., & Osborn, M. (2011). Interpretative phenomenological analysis and embodied, active, situated cognition. *Theory & Psychology*, 21(3), 318–337.

Lave, J. (1988). *Cognition in practice: Mind, mathematics and culture in everyday life*. New York: Cambridge University Press.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. New York: Cambridge University Press.

Lehrer, R., Kim, M. J., Ayers, E., & Wilson, M. (in press). Toward establishing a learning progression to support the development of statistical reasoning. To appear in A. P. Mahoney, J. Confrey, & K. H. Nyugen (Eds.), *Learning over time: Learning trajectories in mathematics education*. Charlotte, NC: Information Age Publishers.

Leont'ev, A. N. (1981). The problem of activity in psychology. In J. V. Wertsch (Ed.), *The concept of activity in Soviet psychology* (pp. 37–71). Armonk, NY: Sharpe.

Linn, M. C., & Slotta, J. D. (2000). WISE science. *Educational Leadership*, 58(2), 29–32.

Marx, R. W., Blumenfeld, P. C., Krajcik, J. S., Fishman, B., Soloway, E., Geier, R., & Tal, R. T. (2004). Inquiry-based science in the middle grades: Assessment of learning in urban systemic reform. *Journal of Research in Science Teaching*, 41(10), 1063–1080.

McDonald, S. K., Keesler, V. A., Kauffman, N. J., & Schneider, B. (2006). Scaling-up exemplary interventions. *Educational Researcher*, 35(3), 15–24.

McNamara, D. S., Kintsch, E., Songer, N. B., & Kintsch, W. (1996). Are good texts always better? Interactions of text coherence, background knowledge, and levels of understanding in learning from text. *Cognition and instruction*, 14(1), 1–43.

Nathan, M. J. (1998). The impact of theories of learning on learning environment design. *Interactive Learning Environments*, 5, 135–160.

Nathan, M. J. (2012). Rethinking formalisms in formal education. *Educational Psychologist*, 47(2), 125–148.

Nathan, M. J. (2014). Grounded mathematical reasoning. In L. Shapiro (Ed.), *The Routledge handbook of embodied cognition* (pp. 171–183). Routledge: New York.

Nathan, M. J., & Alibali, M. W. (2010). Learning sciences. *Wiley Interdisciplinary Reviews: Cognitive Science*, 1(3), 329–345.

Newell, A. (1990). *Unified theories of cognition*. Cambridge, MA: Harvard University Press.

Newell, A., & Simon, H. A. (1976). Computer science as empirical inquiry: Symbols and search. *Communications of the ACM*, 19(3), 113–126.

Palinscar, A. S., & Brown, A. L. (1984). Reciprocal teaching of comprehension-fostering and comprehension-monitoring activities. *Cognition and instruction*, 1(2), 117–175.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. New York: Basic Books.

Pashler, H., Bain, P. M., Bottge, B. A., Graesser, A., Koedinger, K., McDaniel, M., & Metcalfe, J. (2007). Organizing Instruction and Study to Improve Student Learning. IES Practice Guide. NCER 2007–2004. *National Center for Education Research*.

Penuel, W. R., Fishman, B. J., Cheng, B. H., & Sabelli, N. (2011). Organizing research and development at the intersection of learning, implementation, and design. *Educational Researcher*, 40(7), 331–337.

Perfetti, C. A. (1989). There are generalized abilities and one of them is reading. In L. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser* (pp. 307–335). Hillsdale, NJ: Lawrence Erlbaum Associates.

RAND (2004). *Expanding the Reach of Education Reforms: What Have We Learned about Scaling Up Educational Interventions?*. RAND Health.

Robbins, P., & Aydede, M. (Eds.) (2010). *The Cambridge handbook of situated cognition*. New York: Cambridge University Press.

Rumelhart, D. E., & McClelland, J. L. (1986). *Parallel distributed processing: Explorations in the microstructure of cognition*. (vol. 1). Foundations. Cambridge, MA: MIT Press.

Sawyer, R. K. (2005). *Social emergence: Societies as complex systems*. New York: Cambridge University Press.

Schwartz, D. L., Martin, T., & Nasir, N. (2005). Designs for knowledge evolution: Towards a prescriptive theory for integrating first- and second-hand knowledge. In P. Gardenfors & P. Johansson (Eds.), *Cognition, education, and communication technology* (pp. 21–54). Mahwah, NJ: Lawrence Erlbaum Associates.

Simon, H. A. (1962). The architecture of complexity. *Proceedings of the American Philosophical Society*, 106(6), 467–482.

Simon, H. A. (1996). *The sciences of the artificial*. Cambridge, MA: MIT Press.

Songer, N. B. (1996). Exploring learning opportunities in coordinated network-enhanced classrooms: A case of kids as global scientists. *The Journal of the Learning Sciences*, 5(4), 297–327.

Spillane, J. P., Reiser, B. J., & Reimer, T. (2002). Policy implementation and cognition: Reframing and refocusing implementation research. *Review of Educational Research*, 72(3), 387–431.

Stevens, R., & Hall, R. (1998). Disciplined perception: Learning to see in technoscience. In M. Lampert & M. L. Blunk (Eds.), *Talking Mathematics in School: Studies of Teaching and Learning*, (pp. 107–149). Cambridge: Cambridge University Press.

Stokes, D. E. (1997). *Pasteur's quadrant: Basic science and technological innovation*. Washington, DC: Brookings Institution Press.

Tatar, D., Roschelle, J., Knudsen, J., Shechtman, N., Kaput, J., & Hopkins, B. (2008). Scaling up innovative technology-based mathematics. *The Journal of the Learning Sciences*, 17(2), 248–286.

Ur, S., & VanLehn, K. (1995). Steps: A simulated, tutorable physics student!. *Journal of Artificial Intelligence in Education*, 6, 405–437.

Von Glasersfeld, E. (1989). Cognition, construction of knowledge, and teaching. *Synthese*, 80(1), 121–140.

Vygotsky, L. S. (1978). *Mind in society: The development of higher mental process.*

Wertsch, J. V. (1985). *Vygotsky and the social formation of mind*. Cambridge, MA: Harvard University Press.