Foundations of the Learning Sciences

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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' (1987) 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.

I. Principles and Themes of the Learning Sciences

I.1. 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, as well as conducting 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 likewise 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; also CSILE; Scardamalia et al. 1994), 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.

Scale-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 scale-up of effective interventions is critical for education reform, successful scale-up initiatives are rare (Penuel, Fishman, Cheng & Sabelli, 2011). The LS community has, however, been responsible for several successful scale-up efforts, including the above-mentioned *Schools for Thought* (Lamon et al., 1996); Cognitive Tutor Algebra (Koedinger & Corbett, 2006); WISE, or Web-based inquiry science environment (Linn & Slotta, 2000); Quest Atlantis (Barab et al., 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 are more likely to highlight the importance of tailoring the measures and practices to the specific implementation context (Dede, 2006; McDonald et al., 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-implementation-evaluation cycle.

I.2. Scientific and Engineering Approaches to the Study of Learning

The goal for 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 over 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 solely based 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, this volume) are goal directed and

contextualized, and often employ frequent, formative assessment (see Pellegrino, this volume) as part of iterative design-implement-test-redesign methods. This allows for highly responsive, evidence-based course corrections so that it is possible to re-align solutions to suit local constraints, and resolve on-the-fly decisions that are underspecified by prevailing scientific models.

I.3. Influential Theories of Learning

Cognitive Science

Cognitive science is an interdisciplinary field, drawing primarily on cognitive psychology and computer science, that studies *cognition as computation* (Chalmers, 1993/2011). "Computation" is broadly defined to include the many classes of computational systems developed and studied by computer scientists, 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 are most often studied by cognitive scientists 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, it places agency and action in the world, rather than internal mental processing, at its core (Anderson, 2003). 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, this volume) 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 they inhabit. 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 the processes performed by individuals to develop schemas that emerge from interaction and experimentation of the child (the "little scientist") 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* hold that since we each form our own realities there can be no external truth (e.g., von Glasersfeld, 1989). *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 et al., 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 vs. constructivist approaches), and continues to be 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

One of the early theoretical influences on LS was *socioculturalism*--the attempt to explain learning in terms of interactions that take place in social contexts and within communities, rather than in terms of traits or mental processes of isolated individuals (e.g., Vygotsky, 1978). Sociocultural theory is closely aligned with situated action (Greeno & Engeström, this volume) and situated cognition (described above). Learning scientists use these approaches in particular to explaining *informal learning* (Crowley, Pierroux, & Knutson, this volume)--learning outside of schools, whether at home with the family, on the playground with peers, or in apprenticeship settings where youth are learning a trade or some other culturally valued skills (Lave & Wenger, 1991; also see Collins and Kapur, this volume).

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

American pragmatism

The 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; both Piaget and Dewey were contemporaries and both were widely influential in the first half of the 20th century.

Mead, another pragmatist working in the first half of the 20th century, argued that thought was *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. In 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 continue to be influential in LS, particularly among researchers who use qualitative and ethnographic methods to study videotapes of naturally occurring learning encounters (see Goldman, Derry, & Zahn, this volume).

I.4. The Scope of Learning Behaviors

Time Scales of Learning

LS studies learning across levels of space, time, and scale. Figure 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 them is that learning occurs in the context of *designed learning environments* -- classrooms, the home, workplaces, even the psychology laboratory. In each case, the learning environment is an artifact designed in an historical context, in response to cultural constraints and expectations, which is intended to bring about some societally desirable learning outcomes.

Figure 1. Log_{10} time scale of human learning. Adapted from Nathan & Alibali (2010).

Elemental Research

To investigate the range of learning phenomenon 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, 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 some 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 1 to elemental approaches. Methods that draw on learning analytics, such as educational data mining (Baker & Siemens, 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 some 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 necessarily result in a corresponding change in the lower-level description (Sawyer, 2005).

Figure 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.
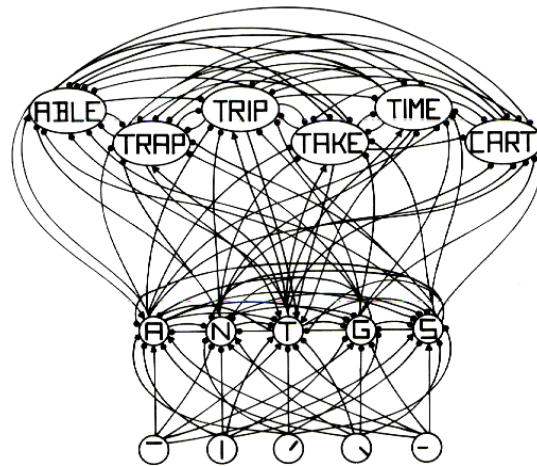

Figure 2. Copied from Rumelhart & McClelland (1986).

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 analyses (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 (Kirschner, & Miyake, 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 analyzing the phenomenon by reducing it to a set of factorable elements (Leont'ev, 1981; Wertsch, 1985).

II. 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 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.
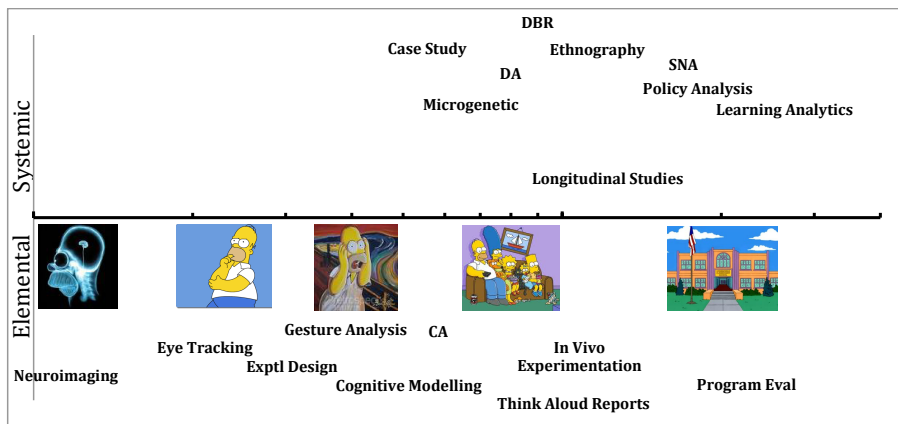

Figure 3. Systemic (above) and elemental (below) research plotted on a logarithmic time scale.

II. 1. 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 thorough 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 provided by practice testing 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 and 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 loads*--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 et al., 1996).

Learning is more effective when learners are encouraged to ground new experiences and concepts to perceptual and motor experiences, language, and to prior knowledge. Some activities that tend to ground meaning, and thus result in more effective knowledge construction, are 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, and participating in project-based collaboration. 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.

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 (Azevedo & Winne, 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 restructure their learning environment. Yet most learners need help doing effective monitoring and self-regulation, and they require feedback in order to verify their own 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 improve their efficiency, retention, and self-monitoring.

II. 2. Systemic View: Evidence-Based Principles of Learning and Design

Systemic research asserts that there can be no separation of interlocutors from their context if one is to rigorously document the phenomena of interest. Context is not simply a container in which disembodied "regularities" occur, but is an integral part of the complex causal field that gives rise to the phenomenon under study. Lave (1988) powerfully illustrates this point when she states that everyday cognition is "*stretched over, not divided among*--mind, body, activity and culturally organized settings" (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 and Sherin, this volume), Conversation Analysis, Interaction analysis, and ethnomethodology. Interaction analysis methodology has been particularly influential within the LS community (Enyedy and Stevens, 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, this volume) is another systemic methodology which documents learning interactions, mechanisms of change, and the influences that bring about these changes (Brown, 1992; Cobb et al., 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, 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 (Hmelo-Silver, Bridges, & Lu, this volume), project-based learning (Krajcik & Shin, 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, this volume) fosters intersubjective meaning making through shared representations and task structure.

There are several potential explanations for how collaboration and argumentation improves individual participant's 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, this volume). Interlocuters must make their knowledge explicit, which helps foster 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, 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 in order to develop and apply collaboration skills, such as turn taking, active listening, critical evaluation, and being respectful of 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" (CTGV, 1997), "Fostering Community of Learners" (Brown & Campione, 1994), and "Kids as Global Scientist" (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 that 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 follow a developmental progression. Skillful pedagogical practices are necessary to encourage and support students' development, and then, just as skillfully, foster the autonomy to become self-reliant. 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, 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* (Collins & Kapur, this volume), 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 being told the information to be learned (Furtak et al. 2012; Hmelo-Silver et al., 2007). Guided inquiry is effective because it elicits many of the most effective learning mechanisms discussed above, 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, 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 et al. (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, this volume).

II. 3. 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, 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 scale-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 first 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, an evaluation 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 refining the design and performance of these subsystems; third, reintegrating modified subsystems back 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 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. 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 system components—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, 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 some quality of system 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 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 enhance components of a complex system than the system as a whole.

Because the behaviors and aims of people differ radically from technological innovations, education may not directly lend itself to functional decomposition methods, per se. But learning environment design may draw inspiration from techniques like functional decomposition for

designing sociotechnical systems. 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 et al., 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 assay 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 re-introduced into the system. Scale-down method emphasizes the important role of the *re-integration process*. The new component design must be thoughtfully re-integrated by practitioners familiar with both the elemental qualities of interest, as well as the particulars of the larger system, and then studied *in situ* using systemic methods.

Programs of research consistent with the scale-down method are emerging, especially in mathematics education. Davenport (2013) used experimental methods, learning analytics, and eye tracking for the redesign of a 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 on concepts and skills, testing practices, and use of worked examples and self-explanation for homework activities are treated as nearly decomposable system components for redesigning the intended, enacted, and assessed curricula, which are then reintegrated by a team of specialists to be implemented in classrooms as a systemic whole. Lehrer and colleagues (Lehrer et al., 2013) 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 et al., 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.

III. Conclusions

The learning sciences is a design science that emerged from a historical intersection of a multiple disciplines focused on learning and learning environment design. Consequently, learning sciences blends research and practice—and views the two approaches as being 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 focus on learning at the level of the individual—such as cognitivism and constructionism. 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. 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.

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