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DESIGN RESEARCH ON LEARNING AND THINKING IN EDUCATIONAL SETTINGS

Enhancing Intellectual Growth and Functioning

Edited by
David Yun Dai

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FROM SMART PERSON TO SMART DESIGN

Cultivating Intellectual Potential and Promoting Intellectual Growth through Design Research

David Yun Dai

> Education seeks to develop the power and sensibility of the mind. On the one hand, the educational process transmits to the individual some part of the accumulation of knowledge, style, and values that constitutes the culture of a people. In doing so, it shapes the impulses, the consciousness, and the way of life of the individual. But education must also seek to develop the processes of intelligence so that the individual is capable of going beyond the cultural ways of his [her] social world, able to innovate in however modest a way so that he [she] can create an interior culture of his [her] own. (Jerome Bruner, 1966, "After John Dewey, What?")

From Smart Person to Smart Design

What makes people intelligent? This question is often interpreted to mean what makes some people smarter than others? The entire history of research on intelligence uses what I call the smart person paradigm; that is, intelligence is a property of the individual mind. We can trace the logic through the use of language: if a person acts *intelligently*, then he or she is *intelligent*, and we might further infer that he or she possesses high *intelligence* (see Lohman, 2001). The reification, of course, requires evidential support. Research efforts have abounded in the past century to pin down exactly what makes one more intelligent than others. What I briefly mention in the following section are but a few distinct examples.

The year was 1978. In an effort to understand how intelligence works, Campione and Brown (1978) drew insights from the performance of children with mental retardation. What they found lacking in these children in a "transfer of training" task was "executive control" (including metacognition), which is responsible for generalizing and deploying routines and strategies in new situations. "As retarded children do not spontaneously fill in gaps in training, their performance gives clues to the kinds of 'gap-filling' which is automatic, or relatively so, for the more intelligent problem-solver" (pp. 287–288). A similar conclusion was drawn from Borkowski and Peck (1986), based on research comparing gifted and regular children on a metamemory task requiring filling in the gaps left by instruction. They found that gifted children did better with fewer trials in the "gap-filling" task and were able to make a far transfer. Similar work based on the then dominant information processing theory led Resnick and Glaser (1976) to propose a definition of intelligence as the ability to learn in the absence of direct or complete instruction. Indeed, the gap-filling capacity was one of the design principles underlying the Aptitude-Treatment Interaction approach (ATI; Cronbach & Snow, 1977; Snow, 1994). This is but only one version of smart person accounts (see, for example, Carroll, 1993; Cattell, 1971; Jensen, 2001).

Now, fast forward to 2005. In an online chess tournament organized by Placechess.com, two amateur chess players as a team became the final winner, defeating some grand masters on their way to the tournament championship. Secret? They "trained" and used three computers to conduct highly skillful analyses, whereas the grand masters were only equipped with mediocre computer programs. Many lessons can be drawn from this event. The most distinct are technological support (computers doing some highly complex calculations and analyses), collaboration (putting heads together, mutual stimulation and evaluation), executive control (deliberation on multiple sources of information and decision-making), and online and offline learning (reflecting on situations and problem solving). To be sure, the role of intelligence in the two amateur players cannot be discounted, which in a way resembles the executive, metacognitive control in the gap-filling research paradigm. However, there is no doubt that the high-level intellectual performance they demonstrated is not possessed by them individually, surely not a property of their minds, but distributed between the two individuals, between the individuals and their environment (conditions and constraints related to chess games) and tools (computer programs) they used. Indeed, there is even an implicit "design" in the distribution of intelligence: taking advantage of what human beings are good at, and what computer programs are good at (see Kasparov, 2007). This and many other social circumstances led Barab and Plucker (2002) to question: what makes an act intelligent; smart person or smart context?

Comparing the intellectual preoccupations in the 1970s and 1990s or 2000s, one cannot help but notice the changes in zeitgeist. Those leading scholars who used to espouse the smart person paradigm back in the 1970s and 1980s have shifted their focus to context (e.g., Brown, 1997; Glaser, 2000; Resnick, 2010; Snow, [illegible]2). Without denigrating the smart person paradigm, it is indeed high time that we consider the problem of "smart design": how intelligent acts

can be enhanced by deliberate arrangements of person–task transactions and environmental support.

Learning and Intelligence: How the Twin Got Separated and Came Back Together

In Alfred Binet's original conception as well as its more contemporary rendition (e.g., Carroll, 1997), learning is about making adaptive changes through experience, and intelligence is about the ability to make adaptive changes, and the growing potential to become increasingly more intelligent through learning. It follows that intellectual development and learning should be closely related: intellectual functioning enables effective learning, and learning should facilitate further intellectual growth. A child who has a habit of trying to figure out things will be smarter over time than a child who is used to getting ideas from others. However, while individual differences in cognitive abilities have always been treated as an important determinant of learning (e.g., Ackerman, 1988; Carroll, 1997; Haier, 2001), the history of research on learning seems to have little to do with enhanced intelligence until recently (Ceci & Williams, 1997; Kyllonen, Roberts, & Stankov, 2008; Perkins, 1995). Why is this? One reason is that for a long time intelligence has been considered genetically determined and biologically constitutional; one can gain knowledge through learning, but one's level of intelligence remains virtually unchanged (see Jensen, 2001). Methodologically, it has to do with the divide between what Cronbach (1957) called two disciplines of psychology. While applied research focuses on psychometric testing and adopts an individual differences approach to the study of intelligence, from Spearman (1904) to more recent efforts (see Carroll, 1993; Deary, 2002), basic research on learning takes a situational approach, aimed at understanding the basic underlying processes and mechanisms, how new responses get strengthened, and gradually become habitual, or how information gets encoded and how it is retrieved for use. Concerns over how active learning enhances an intellectual grasp of matters and achieves its adaptive value in a particular functional context became secondary.

Although Estes (1986) pointed out the role of learning and knowledge in enhanced intellectual functioning, it is not until more recently that intelligence has been conceptualized as contextually bound and developing in nature (Ceci, 1996; Lohman, 1993; Sternberg, 1998). One prominent psychometric theory of intelligence (Cattell, 1971) makes a distinction between crystallized intelligence and fluid intelligence, with the former influenced by learning experiences and supported by knowledge (Hunt, 2008), and the latter more biologically determined and difficult to change. However, recent studies (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008) show that even fluid intelligence can be improved through working memory training. A view of intelligence as distributed between the person, the environment, and tools and resources around, rather tha[illegible]roperty of the mind (Pea, 1993; see Gresalfi, Barab, & Sommerfeld, this volume) further opens the door for more contextual, dynamic, and incremental accounts of how intelligence (i.e., the human mind) functions and develops through learning experiences.

In addition to the parting of the "two disciplines of psychology" (Cronbach, 1957), child development research has also witnessed a long separation of learning and intellectual development. While learning is considered an intake of specific content information, which is processed and stored in long-term memory to be retrieved later, intellectual development is considered as having its own preordained structural properties and development, devoid of any content and context dependency; progression in cognitive functions will occur sooner or later, regardless of what kind and duration of learning experiences or input one might have (e.g., Piaget, 2001). This more or less Cartesian view of development of mental functions as separate from embodied experiences has been challenged in recent years (see Fischer & Bidell, 2006; see also Siegler, 2000, for a discussion of learning redux in developmental research). From a micro-developmental point of view, Kuhn (2002) argued that learning so much resembles development in its complexity, organization, multifacetedness, and dynamic quality, that "we now recognize learning to be more like development" (p. 111).

Taken together, a broader conception of learning, thinking, and intellectual development seems in order, which would fully incorporate the normative notion of learning aimed at optimal intellectual development.

Learning as an Intellectual Act, and Learning Outcomes as Intellectual Growth

Psychology has come a long way in realizing that learning and thinking are fundamentally intertwined, and that, to a large extent, learning is about learning to feel, think, and act in a more sophisticated, intelligent way. As Resnick (1987) pointed out, the seemingly simple task of learning to read involves development of higher-order cognitive functions, such as nuanced understandings of the syntactic and topical nature of a text, and the active process of filling in gaps (e.g., making inferences, building coherence), and detecting discrepancies in making meaning out of a text. Likewise, learning of basic mathematics should be treated as an interpretative (i.e., intellectual) enterprise, so that "mathematics is seen as expressions of fundamental regularities and relationships among quantities and physical entities" (Resnick, 1987, p. 12; see also Resnick, 1988), rather than merely a set of computation routines, created by geniuses and meant to be committed to one's memory. It is time, indeed, to advocate a thinking curriculum (Resnick, 2010) that goes beyond the transmission metaphor of learning and the warehouse model of knowledge (Schank & Cleary, 1995), and integrates what we know about the interplay of knowledge and intelligence to elucidate how knowledge can be built to facilitate good thinking and intellectual growth. [illegible] of learning also includes participation in various domains of

social practice, to experience the world in new ways, to form new affiliations with various groups of people who are doing meaningful work, and to gain resources to prepare for future learning (Gee, 2007).

Although theoretical expositions of learning in the emergent learning science are abundant, with many new proposals and renditions (see Sawyer, 2006), the following three principles are particularly in line with a focus on learning as an intellectual act.

(a) Learning is Perspectival

To learn at the intellectual level is to gain new perspectives or broaden one's intellectual horizon, to feel, think, and talk about a particular topic or act upon a particular class of situations in a more intelligent way (Gee, 2003; Gresalfi et al., this volume). Lampert (1990) distinguished this type of knowledge as knowledge-about, that is, the knowledge of the functionality of a particular method or way of knowing in the larger context of social practice (see also Gee, 2003), which is different from knowledge-of, the knowledge of a particular procedure or concept itself. The perspectival principle also implies that, for a given topic or issue, there likely exist multiple perspectives, each having its own assumptions, logic, and values (Bruner, 1996). The perspectival view of learning highlights the educational value of directing attention and developing sensitivities to various ways of meaning making for adaptive and productive purposes. Affectively, it takes the sequential processes of recognizing, appreciating, and valuing to gain particular perspectives. A child who starts to appreciate a particular way of looking at the world (e.g., through Picasso, Hawkin, or Mother Teresa) is changing his or her mental compass in a fundamental way.

(b) Learning is Instrumental

This principle suggests that learning and doing cannot be separated (Schank & Cleary, 1995); the pursuit of learning always serves some intellectual, practical, and social purposes, be it scientific discovery, engineering a product, or environmental protection. Dewey (1997) put it this way:

> Intellectual organization originates and for a time grows as an accompaniment of the organization of acts required to realize an end, not as the result of a direct appeal to thinking power. The need of thinking to accomplish something beyond thinking is more potent than thinking for its own sake. (p. 41)

Therefore, human motivations are always deeply involved in any socially organized, goal-directed learning activities; it is important, therefore, that students feel "a need to know" (Wise & O'Neill, 2009, p. 90). Learning is optimal when the purposes, structure, and tools of a relevant domain of knowledge are made clear to learners, so that they know why to engage in an activity and how to find and use available tools and resources to achieve their goals. The instrumental principle also implies that contents of knowledge need to be connected so that the learner can see how the parts are linked to the whole in a domain in serving larger functional purposes. The metaphor of "learning your way around" (Greeno, 1991; Perkins, 1995) is powerful in explaining how learning as an intellectual act is to build conceptual understandings of the deep structure or "design grammars" (Gee, 2007, p. 28) that serve to organize seemingly discrete factual and procedural information and turn it into "usable knowledge" (Bransford, Brown, and Cocking, 2000, p. 16). While the history of learning theories was replete with atomists who portrayed learning as a linear accumulation of bits and pieces of knowledge in building a whole (see Hilgard, 1948), the navigation metaphor of learning suggests that learning is an act of navigating complex conceptual spaces and understanding how a particular component is connected with other components in the workings of a machinery, a group of people, an ecosystem, so on and so forth, so as to inform our action in a related practical setting. To be sure, honing skills and consolidating procedural and conceptual instruments take much instruction, training, and deliberate practice over time (recall the 10-year rule in the development of expertise; see Ericsson, 2006). It is important, however, to distinguish between technical proficiency and conceptual understanding in skill development. Technical proficiency reflects the kind of procedural competence that works in a fixed way, thus reproductive in nature. Only conceptual understanding can make one's thinking truly productive in that it enables one to adaptively solve problems for which no ready solution is available (Hatano, 1988). The instrumental view of learning is an antidote to the type of learning that produces inert knowledge, which is a major problem in modern education (Whitehead, 1929). It is the use of knowledge in problem solving that propels extended learning and knowledge building.

(c) Learning Is Reflective

Dewey (1933) takes reflective learning as the central task of education: "The real problem of intellectual education is the transformation of more or less casual curiosity and sporadic suggestions into alert, cautious, and thorough inquiry" (p. 181). Learning is reflective to the extent that the learner reflects on the nature of social practice they participate in, and of instruments and tools they are using or mastering, and of thinking processes and strategies that they are deploying. Reflection, then, means more than metacognition. Rogers (2002) summarized Dewey's delineation of reflective thinking as based on four criteria: (a) meaning-making, [illegible]rigorous way of thinking, (c) community of reflective practice, and (d) a set of attitudes conducive to reflection. Reflective learning naturally leads

to what Gee (2003) called critical learning: "the learner must be able consciously to attend to, reflect on, critique, and manipulate those design grammars [the organizational rules of a knowledge domain or social practice] at a metalevel" (pp. 31–32). What one gains through such reflective thinking is metaknowledge (e.g., knowledge about the nature and process of knowing, thinking, and doing in a domain of social practice) and strategic understandings of when and how knowledge can be used to achieve one's goals. It is worth noting that a reflective stance, like experiencing new perspectives, has both cognitive and affective entailments; as Dewey argued, "there is no integration of character and mind unless there is fusion of the intellectual and the emotional, of meaning and value" (quoted in Rogers, 2002, p. 858; see also Dai & Sternberg, 2004).

To illustrate how these principles are reflected in classroom teaching, I paraphrase an account of a science class quoted by Herman and Gomez (2009, pp. 72–73), with my comments inserted in the brackets:

> In a 9th grade environmental science class, students began by discussing a car on a hot day and the difference between the outside and inside temperature of a car. Then students conducted a lab with 2-liter soda bottles, measuring the temperature differences inside the covered versus uncovered bottles. [*Comments*: A question about an everyday phenomenon drove the discussion and experimentation; students experienced a scientific mode (i.e., a new perspective) of understanding something occurring frequently in everyday life.]
>
> During the post-lab discussion, the teacher probed students on why the temperature increased, and uncovered a misconception that light and heat energy are the same thing, and that they both can pass through a barrier like glass (in the case of the car), or plastic wrap (in the lab). The students were perplexed when their observation of what happened to the covered bottles was at odds with their assumption. [*Comments*: misconceptions and perplexity instigate a need to know, which prompts instrumental learning; students became more reflective on their own beliefs.]
>
> To resolve the puzzle, students read the text about the greenhouse effect and annotated with partners to help dissect the reading. Students discussed what they had found and tried to explain the lab results. Connections were drawn between the covered bottles and the greenhouse effect, tying together the opening example of the car, the experiment, the greenhouse effect, and global warming. [*Comments*: texts were used as a resource for resolving a lingering question; students learned to coordinate evidence and theory in formulating reasoned arguments; they experienced collaboration as a mode of shared inquiry; they made connections between what they did in school and a major challenge in the 21st century, which[illegible]ld lead to significant perspectival, instrumental, and reflective gains.]

Finally, the students returned to their lab group to answer questions that synthesized all of this information and ultimately how the greenhouse effect is the mechanism for global warming. [*Comments*: time for synthesizing, organizing, and reflection.]

In short, these students, through carefully structured activities, were gaining a new way of looking at what occurs around them every day and developing an appreciation of how to think, talk, and act like scientists (perspectival learning), on top of acquiring substantive knowledge. The students' desire for knowledge was driven by making an inquiry that was socially important and personally meaningful; they were building, through the inquiry process, new technical and conceptual instruments for observing, reasoning, and problem solving (instrumental learning). Through discussion, sharing, and reflection on the inquiry process and outcomes, the students were also gaining insights about themselves as learners, about the nature of scientific inquiry, sources and evidence of veridical knowledge; they were also likely to value science when they saw how it improves human conditions and contributes to the welfare of the larger society (reflective learning). This type of learning, which engages thinking and reflection, is in stark contrast to learning as regurgitation and passive absorption of prescribed knowledge, as was apparently the case in the teacher's earlier rendition of the same unit of curriculum (see Herman & Gomez, 2009, pp. 72–73). Consequently, intellectual growth can be defined as follows:

- *Perspectival gains*: Do students gain new perspectives because of the learning experience? Is there evidence of newly acquired or enhanced sensitivities to important matters in the world? Do students come to appreciate and value certain ways of looking at and thinking about the world that they were not aware of before?
- *Instrumental gains*: Do students acquire the kind of foundational knowledge and skills to organize the knowledge in a way that allows them to effectively navigate the problem spaces, including those ill-structured ones? Do they demonstrate the ability to use knowledge and external resources and tools adaptively and productively? Do they show increased motivation to further pursue knowledge in the service of understanding and problem solving that has real life significance?
- *Reflective gains*: Do students show metacognitive gains regarding how and how well they tackle the challenge at hand? Do they show epistemological gains in terms of deep insights into the nature and structure of a domain of knowledge and social practice? Is there evidence of a more critical stance toward information and knowledge claims with respect to its validity and use? Do students show attitudinal changes regarding the value of the knowledge pursuit they have been engaged in?

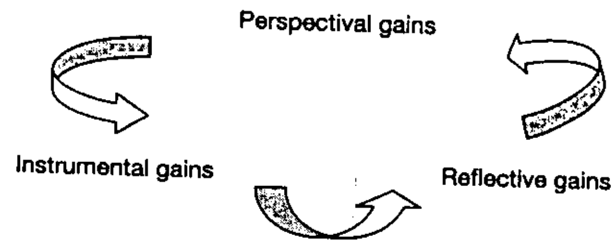

FIGURE 1.1 Reciprocal interaction of perspective, instrumental, and reflective learning.

The three aspects of learning tend to reciprocate and work in a cyclic fashion to form new organization of intellectual functioning. Perspective gains, owing to their framing effect, facilitate instrumental learning. Instrumental gains, by getting deep into the structure and workings of a domain, facilitate reflective learning. And reflective gains further enhance perspectival learning. Viewed this way, learning outcomes should be treated, not in a piecemeal and static fashion, in terms of what one is able to recall or do given a short period of instruction, as the traditional learning and transfer research paradigm implicitly prescribed, but as a dynamic change in the scope, organization, and use of knowledge, and the way the mind is truly empowered to act upon the world (Kuhn, 2002; Schank & Cleary, 1995). In essence, perspectival, instrumental, and reflective learning is by nature generative, adaptive, and productive (Bruner, 1960, 1979). In the same vein, research on transfer should take a more dynamic, developmental view, as evolving representations of contexts and situations in which utilities of certain knowledge are salient (Bereiter, 2002; Royer, Mestre, & Dufresne, 2005).

From this point of view, instruction should be redefined, not as dispensing particular pieces of subject knowledge onto the heads of students, but as supporting and guiding such an intellectual act of making meaning out of presented information and situations and promoting intellectual growth. Optimal teaching, then, involves "smart design," in the sense that (a) learning environments are orchestrated in such a way that the learner's cognitive, affective, and motivational resources are leveraged to optimize intellectual acts and growth; (b) supporting tools and resources are made available to provide affordances and address emergent learning-related constraints and needs; and (c) timely guidance and instruction are provided to enhance meaning making and knowledge building. A smart design, then, is not only producing smart learning in terms of making people smarter in feeling, thinking, and action; it itself is a smart system in its adaptivity to new possibilities and constraints.

Why Design Research? A Need for a New Epistemology of Research on Teaching and Learning

There are profound consequences of such a new conception of learning as involving significant amounts of gaining new perspectives about the world, building instruments and tools for understanding and practical problem solving, and reflecting on knowing and knowledge relative to intricacies and complexities of the part of the world being acted upon.

Learning theory and instructional theory are no longer separate, the former descriptive, and the latter prescriptive (Bruner, 1966; Glaser, 1976; Shuell, 1993). Rather, how instruction mediates learning and thinking at a particular point in development for optimal intellectual growth is a main concern. In other words, instructional design is a normative enterprise constrained by evidence-based principles and reasoning.

Given the nature of design science versus analytic science (Collins, 1992), and the ambition and scope of the "smart design," the traditional research apparatus simply cannot handle the complexity and interactivity of multiple components, and the extended timescale of evolving behaviors of such a system. Taking things apart to see how each component works within a short time frame can be effective up to a point; but, ultimately, putting it all together to see how the system functions as a whole over time entails a new approach. In sum, we need a new methodology that is apt to handle the complexities and responsive to emergent possibilities and constraints involved in designing such a learning environment. Dede (2004) asked: "If design-based research is the answer, what is the question?" (p. 105). It seems that design research is well poised to address the central question of interest here.

While sharing certain common interests and concerns with the traditional research on instructional design and learning–teaching interactions, design research, alternatively called design experiment, design studies, design-based research, espouses a different epistemology. Design research, as Brown (1992) initially envisioned, is "an attempt to engineer innovative educational environments and simultaneously conduct experimental studies of those innovations. This involves orchestrating all aspects of a period of daily life in classrooms" (p. 141). More recently, Collins, Joseph, and Bielaczyc (2004) defined design research as having a design focus and involving assessment of critical design elements, while closely examining "how a design plays out in practice, and how social and contextual variables interact with cognitive variables" (p. 21). It is important to note that switching from the comfortable lab to the messy classroom as a venue for research is not merely intended to carry out theoretical applications in practical settings; it is a strategic move to embrace complexity and find new inspiration from the real-life interactive systems (Brown, 1994; Greeno & the Middle School Mathem[illegible] Project Group, 1998). Whereas the traditional instructional design research is concerned with engineering a sequence of activities in light of how

expertise is developed (e.g., Glaser, 1976) or, in the program evaluation sense, how well a particular instructional program achieves its goals (Isaac & Michael, 1995), design research is concerned not only with building practical models, but also with building theories in situ (Barab & Squire, 2004), or what diSessa and Cobb (2004) called "ontological innovation." What distinguishes design research from the traditional research on instructional designs is the reciprocal interaction of theory, practice, and research in situ, and its iterative, formative, and progressive nature.

Although drawing inspiration from "design" disciplines and professions such as architecture, engineering, and industrial design (Simon, 1981), design work in teaching and learning has both similarities and differences compared with physical design work. Like all design sciences (Simon, 1981), design research in education is concerned with building, testing, modifying, and disseminating new practices and artifacts for particular educational purposes; it has to simultaneously address multiple constraints in achieving its goals; it involves a process of negotiation and bootstrapping, resulting in many cycles of research and development in situ; it uses technical rationality, via building formal models and replicable procedures, as well as reflective rationality, via reflection-in-practice and reflection-on-practice (Schön, 1983). Research evidence to support a particular claim is based not on the rule of falsification, as in natural science, but on optimality of a design relative to achieving its goals, given resources, constraints, and values involved in the design work (cf. Glaser, 1976; Simon, 1981).

However, there are unique properties of design research on teaching and learning. First, design work in education deals invariably with open systems rather than closed systems; the parameters of an open system can never be fully pre-specified, and the end state is not fully determined. In other words, design work in education is by nature an ill-structured domain (Spiro, Feltovich, Jackson, & Coulson, 1991). In contrast, there is complete information for building a house or airplane, both in terms of its structure and the environment in which it will function. Second, design work on teaching and learning involves designing actions and processes for human beings who have their own dispositions to act in certain ways; this constraint is not present for object-based or most agent-based (e.g., designing a robot) design work. Third, as a consequence, any instructional design so developed is a soft design, a design with certain degrees of freedom, as it involves enactment through human actions and interactions. In contrast, a "hard" design would specify every computational detail, leaving little room for variation (other than allowing sometimes for random selection of pre-programmed routines). Taken together, design research in teaching and learning deliberately situates itself at a level of complexity commensurate with that of real-life teaching and learning conditions (Greeno & Middle [illegible]ool Math Project Group, 1998).

Four essential epistemic features can be identified of design research on teaching and learning in general, and designing teaching and learning with the aim of cultivating intellectual potential and promoting intellectual growth in particular.

Authenticity

Authenticity does not only mean that contexts, problems, conditions, and resources set up for learning maintain high degrees of resemblance to those in the real world; the perspectival, instrumental, and reflective learning itself is *authentic* in the sense it carries real meaning and significance to the participants. In other words, there is real human agency in action (perceiving, acting, feeling, and thinking), with real consequences (ends, solutions, and products). The environmental science class discussed earlier illustrates what an authentic learning activity looks like.

Complexity

The teaching–learning system is by nature complex in that there are many interactive elements, social and technical, interpersonal and intrapersonal, that have non-trivial consequences in terms of what actually transpires. Sometimes the complexity can be decomposed to simpler problems or components; for example, constraints specific to individual functioning can be identified and addressed (see Bannan, this volume). But many times, multiple components are responsible for a particular emergent pattern of teaching–learning interaction, which cannot be reduced to any single element acting alone, as interaction can produce emergent properties at the system level.

Emergence

Design work enacted in situ is always "work in progress." Design research on teaching and learning has the dual role of building a theory-driven practical model while simultaneously modifying and refining its conceptualization. Emergence in the design space means that there are emergent properties (new affordances and constraints) during enactment that can only manifest themselves in dynamic situations, and thus need to be captured during the enactment. From an epistemological perspective, emergence as a principle dictates that design research is very much a process of conceptual development and change, from initial conjectures to full-fledged theoretical models. The metaphor of Neurath's boat that Carey (1999, p. 316) used to characterize conceptual changes fits the dynamic, paradoxical nature of design work in situ: building a boat while in the middle of the ocean—water conditions and the functionality of the boat, available materials and tools all dynamically constrain how the boat is built.

Formalism

Design research is supposed to produce a design of some sort. By formalism, I mean both an overt, distinct structure of a practical model, and covert underlying theoretical underpinnings; they both indicate what Gee (2007) called *design grammars*, or what I would prefer to call "design logic." Practically, an instructional model achieves formalism when affordances and constraints of a given learning condition are specified, and the processes by which affordances are realized and constraints satisfied are also explicated to permit the deployment of a set of definable tools and executable procedures in implementing the model (i.e., prototype) in new situations. The design logic here mirrors the process of formalization: an ever-refined understanding of affordances and constraints in such a detailed fashion that a theory can be developed to elucidate underlying components, relationships, and processes within the boundary of a certain teaching–learning situation.

In sum, a smart design aimed at engaging intellectual acts and facilitating intellectual growth in educational settings is situated in authentic contexts, with authentic tasks and purposes. It has a level of dynamic complexity that can only be understood at multiple levels of interactions. Thus design work needs to be tuned into emergent properties and refine its conceptualization iteratively. As a result, practical models can be "formalized" with distinct theoretical underpinnings.

In essence, what I advocate here is a theory of education-based, design-enhanced intelligence and intellectual development. As a matter of fact, much of what diSessa and Cobb (2004) called "ontological innovation" is in line with the notion of design-enhanced intellectual functioning and growth. Such a theory of intelligence would serve the dual goal of making educational innovations that solve recurrent and urgent problems, and building theories that address questions of how intelligence works and why it works at various levels of analysis. Indeed, such an education-based theory of intelligence could easily incorporate those developed in the last century (Campione & Brown, 1978; Resnick & Glaser, 1976), but put them at a proper level of analysis, while pointing out that new educational technology can assist students in performing cognitive (or metacognitive) functions traditionally considered difficult for some individuals (e.g., White & Fredericksen, 2005). In short, *design research is poised to address the complex issue of cultivating intellectual potential in its emphasis on agency, structure, and resources, and its focus on how they work together to produce trajectories of intellectual growth.* It can potentially resolve a deep conundrum of the separation of person accounts and situation accounts in psycho-educational research (Cronbach, 1957, 1975), and the separation of descriptive and normative accounts of development in developmental research (White & Frederiksen, 1998). As a result, such an evidence-based theory would gain more explanatory power than descriptive theories of learning, intelligence, or development.

Challenges to the "Smart Design": A Wicked Problem?

While promoting high-end learning and intellectual growth is a lofty goal, can design research measure up to the task? There are at least three distinct challenges. The first challenge comes from those social pessimists who believe that, when it comes to intelligence, there is not much that educators can do (see Dweck, 1999, for the discussion of an entity view of intelligence). For many of them, transfer, a major concern over whether education can help students extrapolate, generalize, and use what they learn, is epiphenomenal to individual differences in intelligence (Detterman, 1993). This view is in line with early theories of intelligence (e.g., Campione & Brown, 1978; Resnick & Glaser, 1976). More recent theorists also argue that the biologically secondary nature of most human knowledge dictates a more modest view of the active learning and transfer (Geary, 1995), or that the lack of knowledge and expertise fundamentally constrains students' ability to benefit from a constructivist pedagogy aimed at engaging high-level intellectual acts such as problem solving and critical thinking (Kirschner, Sweller, & Clark, 2006). Although there is convincing evidence for the effectiveness of some instructional methods, such as mastery learning, in which highly targeted facts, procedures, and ideas are concerned (e.g., see Bloom, 1984 for learning gains by two standard deviations), solid evidence for learning gains in terms of enhanced adaptivity, deep conceptual knowledge, and critical thinking is still lacking, making some educators and researchers skeptical of such a thing as a "thinking curriculum" advocated by education leaders (e.g., Resnick, 2010). Although obscured in the horizon of many design researchers whose theoretical lens is more social-cultural, the question of ATI (Cronbach & Snow, 1977) and differential treatment effects for individuals still lingers (see Ceci & Papierno, 2005).

The second challenge is epistemological, regarding the efficacy of design research in resolving the issue of enhancing intelligence. The problem of enhancing intelligence through education is an "open problem." Compared with closed problems, for open problems, initial state(s) and goal state(s) cannot be easily defined, and operators to move initial states to goal states are unclear (Kelly, 2009). In other words, the problem may be fundamentally an ill-defined one. It may even represent "a wicked problem" (Kelly, 2009, p. 75), a kind of problem that involves elements or constraints that make its solution potentially unattainable. There are also concerns over methodological rigor, such as lack of control (hence, questionable internal validity) and subjectivity in observing, assessing, and interpreting classroom events, situations, and outcomes, as design researchers are hardly bystanders, neutral to what they are observing. The messiness of classroom teaching and learning itself is a daunting challenge. Should the three-strikes (falsification) rule apply if we have a hard time obtaining solid, convincing evidence in the midst of various "noises" surrounding the classroom (Mayer, 2004)? Are we opening a Pandora's Box methodologically by venturing into the classroom as a main venue for research? Is the enterprise we are pursuing tractable? If it is not tractable, then such a research program will not be sustainable (Lakatos, 1978).

The third challenge has to do with the purposes of design research: is it mainly practical, fashioning innovations that can directly benefit learning and help solve pressing problems, or theoretical, aiming at fundamental understanding? Barab and Squire (2004) and diSassa and Cobb (2004) stressed theory building as a hallmark of design research, while others argue that design research striving for improved practice is by nature eclectic (Kelly, 2009). Of course, we can conceptualize design research as fitting into the Pasteur's quadrant (use-inspired research) in Stokes's (1997) framework, seeking fundamental understanding of effects of some artifacts and practices in a functional context. However, a theoretical orientation would naturally seek explanations that have generalizability as well as coherence, while omitting unnecessary local details and practical constraints, and a practical orientation would be attuned to local conditions and make pragmatic decisions based on available tools and resources. Their priorities can be quite different. Dede (2004) called for a distinction between design and "conditions for success" for a particular design. Thus, a design can be intact itself, even though its practicality may be an issue to be reckoned with in implementation. For example, a design may entail high-level pedagogical content knowledge on the part of the teacher (Shulman, 1987), but that not all teachers are well equipped in this regard does not make a related pedagogical argument less compelling (see also Collins et al. (2004), for the distinction between a design and its implementation). However, if the impetus of design research is to effect changes in the real world (Barab & Squire, 2004), then a design needs to address practical, social, and technical constraints in a direct manner. A "hothouse" design involving intensive resources and support systems may turn out fragile in real classrooms, where resources and infrastructure are not even close to what the designers expect.

Embracing and Untangling Complexity: A Multiple-Level, Multi-Phase Analysis of Design Work

Although dealing with the complexities of classroom life is a daunting task, there are strategies and analytic tools with which to impose order. Greeno and the Middle School Math Project Group (1998) discussed two strategies currently used in research. One strategy is to conduct task analysis of subsystems and components at the individual level, such as cognitive analysis of individual behavior; a problem with this strategy is that there may be emergence of new properties, operators, and outcomes in the higher-order interactive systems that cannot be predicted by the behavior of lower-level components. The other strategy is to study the higher-level interactive systems directly. A drawback is that such analysis might overlook details of individual-level functioning. The two strategies might complement each other. However, an approach that can integrate these two levels of analysis is to propose a multi-level analytic framework that can avoid reductionistic temptations to make individual participants look like isolated islands, while at the same time giving sufficient attention to individual-level constraints on realizing higher-level interaction (Sawyer, 2002).

Levels of Analysis

Any complex system can be seen as a multi-level system (Newell, 1990; Simon, 1981). For the sake of analyzing classroom teaching and learning, I suggest a three-level analytic system, the activity, intentional, and computational levels, with each level having its own properties, constraints, and principles. The first is *activity (interactivity) level*, which is mainly concerned with context, agency, purpose, and structure, and resources revolving around a learning activity. At this level, design analysis is strategic: decisions have to be made on (a) what are desired goal states; (b) what kind of tools and resources are needed to achieve the goal states; and (c) how should learning be organized and structured to achieve the goal states?

As the design work gets to psychosocial processes, the intentional-level analysis will be introduced; that is, how affordances of a learning activity are perceived and acted upon by the learners individually or interactively in a group setting, and what kind of intentional-level action and interaction needs to be activated. Note that the three aspects of learning, perspectival, instrumental, and reflective, all involve intentionality or directed consciousness in the form of affects, desires, and thoughts (Searle, 2004). Active learning and meaning making are interpretative acts, and thus the design analysis needs to preserve its unique subjective properties, such as intention, positional identity, and intersubjectivity. For example, Brown and Campione's (1994) postulation of shared inquiry (e.g., seeding and migration of an idea) is meaningful only under the assumption of a common intellectual space traversed by many, and the commitment to norms of practice shared by a group of participants (see also Bereiter & Scardemalia, 1993; Zhang, this volume). Learning as critical interpretation (Lehrer & Pfaff, this volume), as active investigation and the development of dispositions to think and act (Gresalfi, Barab, and Sommerfeld, this volume), as participation and identity development (Polman, this volume), all operate at the intentional level.

As design analysis gets further down to algorithmic or computational level, then the issue of how intentional-level actions are realized (or fail to be realized) at the individual level can be further elucidated. In other words, how instructional mediation plays out at the psychological level, and how individual-level enabling and constraining factors interact with instruction and social interaction can be identified. Indeed, we can discuss constraints imposed by cognitive architecture (Kirschner et al., 2006) and its functional properties (e.g., comparing architectural ideas by Barsalou, 2003; Glenberg, 1997; Sun, 2007; Sweller, Kirschner, & Clark, 2007).

The utility and importance of discerning levels of analysis in design work becomes clear when we realize how we can be caught up by the failure to pay due respect for unique properties and principles at each level of analysis. In a recent debate on pedagogy or instructional approaches (Tobias & Duffy, 2009), "constructivists" and "instructionists" talked past each other (Duffy, 2009; Wise & O'Neill, 2009) precisely because they discuss issues at the different levels of analysis. While constructivists espouse more ambitious goals of promoting active learning and critical thinking and developing the person, instructionists are more worried about the lower-level constraints, such as lack of knowledge and cognitive overload. Each level of analysis has its own properties and principles that need to be heeded; however, to argue that lower-level constraints can be a basis for prescribing higher-level learning goals amounts to arguing that physicists know better than civil engineers about how to build a bridge.

Multi-Phase Design Architecture

In addition to levels of analysis, complexities of design work can be managed by segmenting different components and phases of design work, each tackling a particular aspect and phase of learning activity. For instance, Calfee and Berliner (1996) used *someone (teacher) teaching something (content) to someone (learner) else in some setting (context)* as a basic script of the dynamic teaching–learning system. The "How People Learn" framework focuses on four main components as central issues of designing learning environments: community, learner, knowledge, and assessment (Bransford et al., 2000). There seem to be two critical issues all design work has to deal with. The first is how instruction can be responsive and adaptive to behavioral, cognitive, and motivational characteristics demonstrated by a learner or a group of learners (Snow & Swanson, 1992); the second is how to balance and integrate content representations and thinking processes in teaching (Baxter & Glaser, 1997) and assessment (Anderson & Krathwohl, 2001). Figure 1.2 presents an architecture of design research on teaching and learning that honors the conventional wisdom and practice in educational psychology, while emphasizing the dynamic emergence of theories and models of teaching–learning grounded in practice, research, and reflection in situ. As Glaser (1976) envisioned in probably the earliest exposition of design research in instructional psychology:

> The design process essentially involves the generation of alternatives and the testing of these alternatives against practical requirements, constraints, and values. This is not done in a single generation-and-test cycle, but through an iterative series involving the generation of alternatives, testing them (through actual small-scale studies or through simulation), describing revised alternatives, testing them, and so on. (pp. 7–8)

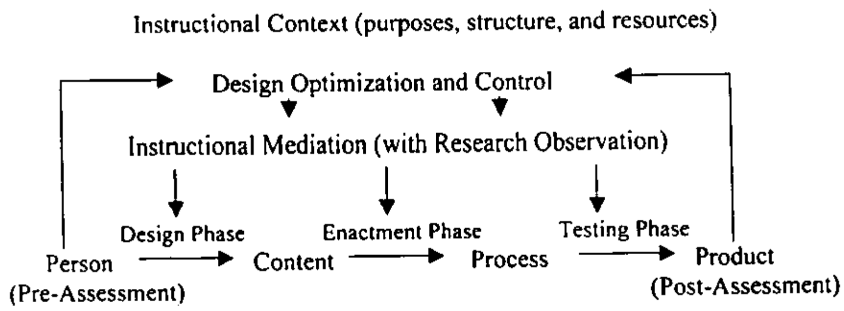

FIGURE 1.2 An architecture for design research on teaching and learning.

In this flowchart (Figure 1.2), Instructional Context serves as an overarching guide for design work on goals, specific components, structure, interactions, and resources. The arrows indicate the direction of information flow in design work. The information flow starts with Person (the learner), individually or as a group, which directly informs instructional mediation of the person–content interface. This is the "design phase," typically occurring offline (i.e., before enactment): how to represent subject matters and structure the learner–content interaction in a way conducive to the desired learning outcomes.

As the information flows from Person and Content to Process, design research enters the "enactment phase": designed learner–content interaction occurs, and related instructional mediation is carried out "online" (in real-time teaching) by teachers or teachers/researchers. Simultaneously, design researchers document what thought processes are engaged through what kind of instructional mediation, and how content is represented and processed.

When Process leads to Product, the design work enters the "testing phase": how well the designed interactions work, as manifested by learners' overt behavior and performance. This information would flow back to Design Optimization and Control to create feedback and feedforward loops, and another cycle of design work starts for optimization and improvement of a design and a modified and refined underlying theory. In the following section, I will discuss each component in the context of enhancing intellectual functioning and promoting intellectual growth, or, more specifically, how perspectival, instrumental, and reflective learning can be engendered through teaching–learning interactions and realized at the individual level.

Instructional Context

Instructional contexts are mainly concerned with goals, structure, and resources for designing a learning environment and sequence of learning activities (an activity-level analysis). Thus, any design has a normative side (what kind of

knowing and knowledge is desired and valued in the learning enterprise), a pedagogical side (how learning should be structured and mediated to achieve the set goals), and a pragmatic side (what resources are available for that purpose).

The following questions are central when we try to integrate learning with concerns over intellectual gains: What is the nature of the subject matter we are teaching vis-à-vis the current level of the child's knowledge and thinking, how it is connected to the larger social world in which children live, and how it might broaden the intellectual horizon of the child in question. A recurrent debate in this regard has been between those who insist in teaching basic knowledge and skills and those who advocate teaching for deep understanding and higher-order thinking. Siegler (2001), for example, questioned whether it is realistic to teach grade school children for deep disciplinary understanding of math and science (see also Kirschner et al., 2006).

There are three root metaphors of the structure of learning, transmission (or acquisition), construction, and participation (cf. Greeno, Collins, & Resnick, 1996), which help organize learning in pedagogically different ways. For those who promote "higher literacy" and believe that students need to know that "mathematics, biology, history, physics, and other subjects of the school curriculum are distinctive ways of thinking and talking" (Wineburg & Grossman, 2001; see also Gee, 2003), the notions of learning as participation and (knowledge) construction are central, though social transmission of knowledge is also meaningful in the form of cognitive apprenticeship. How we can teach the mind to respond to new situations more adaptively and critically is at the heart of cultivating intellectual potential and promoting intellectual growth. For this purpose, learning of disciplinary content in proper contexts of use is instrumental for supporting such intellectual growth.

Person as an Enabling as Well as Constraining Factor

The person (the learner) is both an agentic presence and constraining factor for design work. Under the cognitive framework or acquisition metaphor, the person is often conceptualized as providing an initial state, and instruction is designed to bring the person from an initial state to a goal state, however defined (Glaser, 1976). Researchers using the participation metaphor of learning conceptualize the learner in terms of what kind of entry (timing, medium, and support) is appropriate for ushering the person into the realm of a particular social practice, be it mathematics or literature.

Many putative learning-related constraints have been proposed, most of which have to do with abilities and prior knowledge (Snow & Swanson, 1992). A recurrent theme summarized by Newell (1990) is the preparation–deliberation trade-off: the more offline preparation (e.g., more prior knowledge), the less the demand on online deliberation. Cognitive load theory (CLT) deals with the trade-off in a more elaborate way (see Plass, Moreno, & Brunken, 2010). Arguments against inquiry-based or more constructivist-oriented teaching are often based on the assumption that students don't have the necessary knowledge preparation to engage in high-level thinking and problem solving (Kirschner et al., 2006; see Tobias & Duffy, 2009). With respect to levels of analysis, the arguments typically conceptualize constraints as located at lower-level mechanisms and operations, such as working memory capacity limits and lack of cognitive schemas to reduce the cognitive workload. Regarding this objection to higher-level meaning making in learning, the question is how much does a person have to know about a domain before he/she can develop deep insights into the "modus operandi" of a domain as a form of social practice? Here, the distinction between perspectival and instrumental learning becomes useful. It seems that gaining a new perspective through experiencing things differently or in more specialized and principled way (knowledge-about; see Lampert, 1990) may not be as demanding in terms of prior knowledge as building and practicing "instruments" for problem solving (knowledge-how). A key pedagogical strategy is to start informally and experientially (e.g., developing an intuitive basis for deep understanding, using metaphors and other means; see Lehrer & Pfaff, this volume) and move gradually toward formalization (Bruner, 1979; see also Bransford et al., 2000).

Individual differences in cognitive and affective functions are often used as a basis for differentiated treatment. Indeed, the ATI research is built on this premise (Cronbach, 2002; Cronbach & Snow, 1977; Snow & Lohman, 1984). Glaser (2000) suggested that we move away from the abstract notion of "aptitude" and take a more diagnostic approach regarding what one can or cannot do. To combat a static, unqualified notion of "aptitude," Snow (1992) proposed aptitude–situation as a union; that is, aptitude is always relative to situations. This more proximal, situational construal of aptitude makes it possible to encourage and foster active and critical learning and intellectual development regardless of their "entry" level, while addressing whatever constraints and impediments might be present vis-à-vis the learning task at hand (see Bannan, this volume, for a detailed account of designed interventions with twice exceptional children).

There is an increasing realization that children should be considered not merely as a constraining factor, but as an enabling one, a resource to draw on. The fact that the human brain is predisposed to predict patterns, even when an array of stimuli is random (Gazzaniga, 2000), and that children as young as five or six years old are routinely and spontaneously engaged in conscious meaning making of their experiences of the world (e.g., making "representational redescription"; Karmiloff-Smith, 1992), makes it clear that learners should be an active part of design work, rather than sitting at the receiving end, "acquiring" the knowledge and skills prescribed by others. The two examples used by diSessa and Cobb (2004) to demonstrate "ontological innovation" in design research, metarepresentational competence and sociomathematical norms are cases in point. The former refers to a body of knowledge students bring to bear upon the learning materials in a

and the latter refers to norms of mathematical discourse that encourage intellectual autonomy in taking part in mathematical practice. Both are instances of agency emergent from classroom discourses that the design researchers leveraged for more advanced academic and intellectual development. That learners can effect a more productive learning environment by acting on the subject matter intelligently, critically, and creatively should be a major consideration in design. It brings opportunities as well as uncertainties to design work (see Engle, this volume; Gresalfi et al., this volume; Langer, this volume; Zhang, this volume).

Content Representation: Designing the Person–Content Interface

Design work in this phase is basically designing the person–content interface. It involves analysis of affordances and constraints: what a situation enables and affords the learners to do and accomplish, and what constraints need to be addressed in order to materialize these affordances. The key issue to be addressed is representation, because how students interact with an instructional situation is mediated by perceptions and interpretations of that situation. This is a distinct intentional-level analysis. By content representation, I mean not only representation of the subject matter, but also that of a learning situation (e.g., in what context and how a topic is introduced, and a problem is presented, and what is the purpose of introducing the topic or problem), as the latter can influence students' perceptions and representational strategies regarding the former.

The normative question of treating learning as an intellectual act is how an instructional situation and its informational content can be designed to induce perceptions and interpretations conducive to perspectival, instrumental, and reflective learning.

For this purpose, both the medium and substance of representation are important. Medium concerns *how* information is presented and represented, and substance concerns *what* is presented and represented. For illustration purposes, we can roughly classify media as text-based, discourse-based, and action-based, and substance as content knowledge (facts, concepts, and theories, etc.), reasoning schemas and strategies (proportional vs. causal reasoning, use of metaphors and analogy, inferring design grammars, etc.), and complex problem solving (cases, critical instances, projects, etc.). Putting them in a larger instructional context, a curricular/instructional activity has three levels of representation: (a) representation of subject matter as part of the curriculum content in its purposes, structure, and functionality; (b) representation of the informational content as part of a larger body of domain knowledge and its epistemic value and practical utilities (i.e., Popper's World 3; see Popper, 1972); and (c) representation of content being learned as a cultural way of knowing and part of social practice that produced this body of knowledge (i.e., recognizing it as a particular kind of socially always involves *recognizing* various distinctive ways of acting, interacting, valuing, feeling, knowing, and using various objects and technologies, that constitute the social practice" (Gee, 2003, p. 29; italics original).

Medium and Message

Text-based representations include a variety of verbally mediated forms of communication aimed at disseminating information and knowledge or presenting a particular argument. A text can contain propositions, facts, claims, narratives, or expositions, from which meanings (structures, functions, relationships) can be drawn and made about the world (states of affairs, human conditions, etc.). However, text-based representations are for most part mediated by language and, to a lesser degree, pictures. Text comprehension (e.g., critical reading) is an act of reasoning and meaning making par excellence, involving critically interpreting and understanding the underlying logic of a text vis-à-vis a particular topic. Texts are most frequently used for representation of a culturally created body of knowledge, World 3 in a Popperian sense (Popper, 1972). One example is concept-oriented reading instruction (Guthrie, Wigfield, & Perencevich, 2004). However, texts can also be built to represent the cultural practice that produces knowledge. Palincsa and Magnusson (2001), for instance, reported their research on second-hand investigation by deliberately building a text in the form of a scientist's notebook, mixing genres of narrative, exposition, description, and argumentation, to represent scientists' doing, feeling, and thinking in a scientific domain. Learners, while reading the notebook, would mentally simulate the thought processes (i.e., emulating, vicariously, a modus operandi) scientists go through, and gain insights into the nature and processes of scientific inquiry. The context for the use of texts becomes a critical consideration in such instructional contexts, as is also the case in the teaching of the greenhouse effect discussed earlier, where text material is used as a tool with which to understand real-world problems students encountered. In other words, a text, and the just-in-time knowledge it presents, is used instrumentally to understand and solve a problem.

Discourse-based representations refer to representations engendered during or after significant amounts of teacher–student, student–student communication and interaction. Discourse-based representations are important because most of academic learning involves interpretation or sense making, namely delving into the various realms of meanings (Gee, 2003; Phenix, 1964). Resnick's (1987) teaching of mathematics as an ill-structured discipline and Lampert's (1990) pedagogy of engaging fifth graders in mathematical guesses were early examples of building deep understanding of a topic through discourse-based representations. In fact, they afford metarepresentation of underlying logic and "rules" for generating an[illegible]tifying knowledge claims (Kuhn, 2002). Lehrer and Pfaff's (this volume) use of measurement as a basic metaphor for understanding rational [illegible]-based tool frequently used to engage students in

"epistemic conversation." Langer's (this volume) envisionment-building in literature and social studies, and Zhang's (this volume) creative knowledge practice also rely heavily on discourse-based representations.

Action-based representations are based on situated inquiry and problem-solving activities. Guided discovery, problem-based and project-based learning, skill-based simulations and games, all have a distinct action component in the sense of having a problem to solve and a task to accomplish. An action may involve texts and discourses but has added value in its affordances for real-time, in situ actions and representations (and metarepresentation) of a particular way of knowing and thinking as a professional practice (Gee, 2003; Shaffer, 2004). Action-based representations are embodied because such representations are ingrained in actions, motivations, perceptions, affects, attitudes, and values, rather than taking the abstract, symbolic form. Although the efficacy of action-based instructional activities for students who have limited knowledge and skills to work with is questioned (Kirschner, 2009), it can be argued that they provide an experiential basis for grounding the otherwise decontextualized abstract concepts and theories. As Barsalou (2003) suggested, an action-based dynamic conceptual representation can be tailored or fine-tuned to "the constraints of situated action" (p. 553), thus more easily activated to support future action. The learning conditions created in the environmental science class discussed earlier afford such an action-based dynamic conceptual representation of "greenhouse effect" that enables the students to act upon the knowledge (i.e., transfer) more readily and effectively.

A design may mix two or more forms of medium, as is usually the case with most designs. A critical question for perspectival, instrumental, and reflective learning is *how to put a particular content in a larger context so that representations become potent for connections to its perspectival reference and instrumental value.* An age-old issue in learning theory is the part–whole problem. Hilgard (1948) delineated the history of learning theories as divided between those who view learning more atomistically, as installing building blocks one by one to build an ever more complex repertoire of knowledge and skills, and those who view learning as a process of mapping out the structural whole in which various pieces of knowledge will find their respective place (see also Perkins, 2010). Without taking a too polemic view on the debate, it can be argued that situated actions coupled with guided inquiry may engender representations that are intellectual in nature; that is, they afford metarepresentation of knowledge as the result of human endeavor to understand and change the world.

Process and Instructional Mediation: Engineering a Sequence of Learning Activities

This is an enactment phase of design work. The key question is how to engineer a sequence of learning activities that maximally utilize personal, technological, and social resources to achieve perspectival, instrumental, and reflective gains, while at the same time addressing possible developmental, social, and individual difference constraints regarding cognitive readiness, affective valence, and motivational inclinations. This is where the person, content, and context issues need to be integrated and addressed simultaneously: (a) How to leverage students' knowledge, abilities, and motivations while addressing potential constraints at the individual and interactive levels (Person); (b) How to direct attention and thinking to engender proper content representations in the service of overall learning goals (Content); (c) How to orchestrate important design elements of classroom teaching (pedagogical tools, technological support, social organization of learning) to enable optimal learning conditions for intellectual growth (Context). In short, while early phases of design work may take things apart to see how they work separately, in the enactment phase one has to put everything together to see how it works as a whole. Most important social-contextual, interactive factors (activity level) and psychosocial variables (intentional level) in a given learning situation are now clearly defined, substantiated, and operational at this stage of design work, and enactment will ultimately get the computational level in terms of execution and detailed implementation. They set the stage for the work of instructional mediation.

Instructional Mediation: Engage, Guide, and Organize

Instructional mediation is the real-time mediation of the person–content–context interaction. Instructional mediation of learning as an intellectual act can be seen as a pedagogy of enhanced thinking: *how to engage, guide, and organize learning and thinking in the direction of gaining new perspectives, mastering new instruments, and fostering new reflective insights*. The mediation process can be explicit (e.g., taking the form of direct teaching or guidance), or seamless (e.g., embedded in problem-solving activities); it can be a built-in feature of an instructional medium (e.g., how a text or game is structured to engage, guide, or organize active and reflective learning), or through a human agent (e.g., the teacher) (Dai & Wind, in press; Palincsa & Magnusson, 2001). Instructional mediation inevitably utilizes three resources: pedagogical tools, technological support, and social organization in addressing learner-related, content-related, and context-related constraints. In the following, I briefly discuss how gaining perspectives, mastering instruments, and fostering reflective insights have their own distinct entailments, and how each can be engaged, guided, and organized, with a caveat that they work in a reciprocal, cyclic fashion.

Instructional Mediation of Perspectival Learning

In line with ecological psychology, the essence of perspectival learning is the education of attention and perception (Gibson, 1977). Although working memory capacity and cognitive load are distinct, relevant issues for learning new materials

(Plass et al., 2010), Saariluoma (1992) found from his research on chess that a more critical element in performance errors is perceptual (apperceptions) in nature, rather than memory capacity. In other words, learning involves a reorientation of attention and restructuring of perception, or reorganization of one's interpretative apparatus (Piaget, 2001; Sinatra & Pintrich, 2003). Because of the perceptual nature of perspectival learning, affect or feeling becomes a crucial factor. The moment one says "it makes sense" or "how come this happened?" indicates a state of feeling and consciousness that is anything but emotionally neutral. Two constraints follow: people only try to actively interpret a situation when there is perceived novelty or perplexity (Hatano, 1988); and perspectival gains would not occur unless a learner is open to changing beliefs and values (following the recognize–appreciate–valuing sequence).

Instructional Mediation of Instrumental Learning

Learning is instrumental in that learning helps one achieve intellectual, social, and practical goals of solving problems relevant and meaningful to the learner. In the greenhouse lesson cited earlier, the teacher engaged students in figuring out the temperature changes inside a car or soda bottles, thus creating "a need to know" (Wise & O'Neill, 2009). A major pedagogical strategy for cognitive and affective engagement is to position learners to acquire content knowledge that has a direct bearing on important, real-life circumstances (Barab, Gresalfi, & Ingram-Goble, 2010). Besides engagement, guiding attention, reasoning, and organizing problem solving through modeling, scaffolding, and granting authority, and collaboration is what most inquiry-based learning models highlight (see Hmelo-Silver, Duncan, & Chinn, 2007; Schmidt, Loyens, van Gog, Paas, 2007; White & Fredericksen, 1998; 2005; see also Engle, this volume; Zhang, this volume). Consider the "gap-filling" notion of intelligence discussed in the beginning of this chapter: children who are spontaneously engaged in coherence-building, or bridging-the-gap self-explanations, are seen as more intelligent than those who are not. If so, instructional mediation for those less prone to fill in the gaps can take the form of encouraging inference-making and self-explanations, which enable the learners to develop a disposition to seek explanation and consequently a schema for reasoning about a given class of phenomena or events (Siegler, 2002). Even constraints that sit deeply in the learner's cognitive infrastructure (e.g., attention deficit) can be remedied to some extent by external, technology-supported systems (see Bannan, this volume), analogous to prosthetic devices for the physically handicapped. To be sure, instrumental learning means mastery of conceptual and technological instruments and tools that take many years of deliberate practice to build and solidify (Ericsson, 2006), and the nature of instrumental learning as progressive deepening (de Groot, 1978; Newell, 1990) may put further constraints on how fast one can achieve technical proficiency and expertise in a domain. Yet, the instructor should never lose sight of their real-life utilities or instrumental value as supporting problem solving (Shulman & Quinlan, 1996).

Instructional Mediation of Reflective Learning

To use Schön's (1983) framework, both reflection-in-practice and reflection-on-practice can be instructionally mediated through engagement and guidance. For example, in epistemic games that mimic professional practices (Shaffer, 2004), Shaffer and his colleagues deliberately built a reflection cycle into the gameplay, so that the epistemological grounding of such professional practice can be reflected upon. White and Fredericksen (2005), in their work on inquiry-based learning in science, developed a technology-based support system designed to enhance metacognition. In his mathematical teaching, Lehrer (Lehrer & Pfaff, this volume) engaged students in an epistemic conversation, meant to be reflective on the fundamentals of mathematical thinking. Viewed in a broader context of learning, reflective learning is a natural consequence of instrumental learning (see Figure 1.1). People engage in reflection, not because of its intrinsic interest, but because of the consequentiality of learning (Barab et al., 2010; see also Derry & Lesgold, 1996, for reflective learning in training settings).

Product: Assessing Learning, Developing a Prototype, and Building a Grounded Theory

If the enactment is a process of orchestrating and engineering, the transition from a focus on process to a focus on product indicates a testing phase for design work. Here, the term "testing" has three dimensions: (a) whether the process produces a desired state or trajectory individually or collectively (the effectiveness criterion); (b) whether the process produces a design prototype that has well-defined components and procedures that make it scalable and applicable to a range of instructional situations (the practicality criterion); and (c) whether the process produces a grounded theory that has all constructs and interrelations well defined and assessed and has a level of generality that enables it to explain how learning can be optimized to support thinking and development (the validity criterion).

Does the Process Produce a Desired State or Trajectory (the Effectiveness Criterion)?

Current assessment practices for effectiveness of a program are still in the transition from a traditional approach that assesses discrete pieces of knowledge to a more for[illegible]ive, diagnostic approach that aims to enhance learning (Shepard, 2000). Fo[illegible]ssment of intellectual growth, what one learned serves the purpose of thinking more intelligently about a topic. At least the following taxonomy of intellectual gains can be discerned: (a) foundational knowledge (facts, procedures, and concepts, and goals of a discipline or domain of social practice); (b) conceptual understandings (reasoning schemas at a more complex level) regarding a subject or domain; (c) meta-awareness of the epistemological grounds of the knowing process and knowledge claims; (d) the transformation and productive use of knowledge for intellectual or practical purposes (i.e., problem solving); (e) refined habits of mind, such as a critical stance, a disposition to reason, seek explanations and make educated guesses, to extrapolate, to suggest viable alternatives, and probe for further understanding, to engage in counterfactual thinking (suspense of disbelief), or, simply put, to think more intelligently (Gresalfi et al., this volume; Halpern, 2008; Perkins & Ritchhart, 2004). The traditional psychometric approach is inadequate in dealing with the challenge (see Moss, Pullin, Gee, & Haertel, 2005, for a sociocultural argument against psychometric perspective on testing); yet, without some metrics of performance and behavior, making claims about positive changes becomes difficult (see Kelly, this volume). At any rate, the assessment of learning gains of interest would have to take innovative approaches, capturing these qualities dynamically in situ, rather than in a paper-and-pencil task (see Gresalfi et al., this volume; Shute & Kim this volume; and Zhang, this volume; see also Gee & Shaffer, 2010). Assessment in design research is by nature formative, not only in the sense of improving design, but also assisting in further defining the parameters of a problem that a design attempts to address.

Does the Process Produce a Design Prototype that has Well Defined Components and Procedures that Make it Scalable and Applicable to a Range of Instructional Situations (the Practicality Criterion)?

The second criterion determines whether a design is practically viable and implementable. It is still open to debate as to the degree in which a design needs to be "proceduralized" so that instructors can implement it with high fidelity, or should be principle based and remain flexible for adaptation to local situations (see Dede, 2004; Engle, this volume; Zhang, this volume). The issue concerns the extent to which a design can realize full technical rationality or formalism in terms of specifying all details of implementation from the social-interactive level all the way down to the psychological level. Given that we still don't know much about how to engineer psychological processes in an algorithmic fashion, a design may have to stay at a level that is not fully specified through technical rationality. Therefore, a fair amount of reflective rationality is still needed on the part of implementers to materialize a design that, in many respects, remains principle based and demands critical (and sometimes creative) interpretations in implementation. Another issue is the extent to which a design can maint[illegible]s quality and integrity while remaining realistic for implementation, for exampl[illegible] not taking inordinate amounts of resources and expertise. Dede (2004) alerted design researchers to a distinction between a design and its conditions for success. There seems to be a trade-off between idealism and realism.

Does the Process Produce a Grounded Theory that Has All Constructs and their Interrelations Well Defined and Assessed and Has a Level of Generality that Enables it to Explain How Learning Can Be Optimized to Support Thinking and Development (the Validity Criterion)?

Design research ultimately aims at producing evidence-based claims that potentially change the existent educational practices (Barab & Squire, 2004). Moreover, it generates theoretical ideas that illuminate important parts of education and instructional practice and thus deserve the label "ontological innovations" (diSessa & Cobb, 2004). Design research aimed at high-level intellectual functioning and growth should do no less. At a minimum, it needs to specify person-based, content-based, and context-based affordances for, and constraints on, learning as an intellectual act in a way that informs instructional mediation, leading to social and psychological processes that materialize affordances in terms of enabling perspectival, instrumental, and reflective gains. To the extent it illuminates how feeling, thinking, or acting is (or can be) engaged, guided, and organized in authentic learning and performance situations, it becomes an education-based, fully integrated theory of learning, intelligence, and intellectual development.

Process Optimization and Control: Design–Test–Modification Iteration and Theory Building

This is the metalevel, executive function of design work. Part of the executive function is control: how to manage the temporal, socially and psychologically dynamic activity of learning that involves interactivity of multiple agents and resources within a certain temporal and social boundary. Historically, researchers preferred to use simple units of analysis that contain minimal elements for enhancing internal validity (i.e., doing controlled experiments; Campbell & Stanley, 1966). Design research deliberately uses a unit of analysis that encompasses a broad range of social and psychological parameters and has a high level of complexity. A strategic issue design researchers have to wrestle with is how to define and manage the boundary of a design, open and responsive to important clues and new leads, while not overstretching to the point of unmanageable complexity. For example, should a design involve institutional support, such as teacher training and capacity building? Earlier, I elaborated on instructional mediation. But what about teacher learning and growing with students? Such a component [illegible] cultural and institutional changes of a school and complicate

implementation. However, without such a component, a design may be fragile and unsustainable in real classroom settings.

Beyond control and management issues, the main purpose of the executive function of design work is optimization, a prominent feature of design work (Glaser, 1976): how a system can be attuned adaptively to emergent constraints, properties, and new affordances, while maintaining an initial principled stance. The optimization mainly relies on two mechanisms: feedback and feedforward. Feedback mechanisms rely on information that flows from person, content, process, and product to inform effectiveness of learning vis-à-vis set goals and objectives, including identifying emergent person-related, content-related, and process-related constraints (see Polman, this volume). Feedforward mechanisms rely on information from the person, content, process, and product to envision emergent affordances and new possibilities (e.g., students' newly found or acquired skills create new learning opportunities). It should be noted that both feedback and feedforward mechanisms are not merely to improve practice; it is a process of theory building as well. In fact, the "ontological innovations" diSessa and Cobb (2004) elaborated on are all based on feedforward mechanisms, inventing new theoretical constructs that become a leverage point for enhancing intellectual functioning (see also Zhang, this volume).

Significance of This Line of Work

In this introduction chapter, I attempt to delineate a history of how we have come to a point where it is viable to think about learning, teaching, and thinking as intertwined rather than separate issues, and how design research may help build an agenda to promote intellectual growth and formulate an education-based theory of intelligence and intellectual development along the way. A perusal of the literature on design research will reveal that most prominent concerns of design research have been on students' deep conceptual knowledge and higher-order thinking; yet the design research community remains silent regarding the challenges from the psychometric research that shows distinct individual differences in intellectual functioning and development, or from those skeptics who argue that the constructivist movement aimed at promoting higher-order thinking in education has yet to produce creditable supporting evidence beyond the rhetoric (e.g., Kirschner et al., 2006; Mayer, 2004; 2009). There are three imperatives that make this line of work important: theoretical, empirical, and practical.

The Theoretical Imperative

Intelligence has for a long time been seen as a property of the mind, a trait possessed by the person. Perkins (1995) concluded that all extant intelligence theories fall into three classes: the first kind, neural intelligence, emphasizes the role of biological underpinnings for high-level functioning; the second kind, experiential intelligence, emphasizes domain experience as a basis for high performance; and the third kind, reflective intelligence, stresses the role of the reflective guidance in enhanced intellectual functioning. While neural intelligence is presumably less malleable, experiential and reflective intelligence can be enhanced by social interventions. Also, in the spirit of distributed intelligence (Gresalfi et al., this volume), design research has the potential to contribute to "smart design," even a new kind of theory of intelligence, fully situated in education settings, use-inspired, grounded in empirical evidence of realized intellectual potential and growth, reflecting optimal design as much as power of mind. In other words, can we go beyond the Flynn Effect (Neisser, 1998) to reach a new level of sophistication in intelligent designs and designed intelligence? To social optimists as well as pessimists, this is a test of nature and nurture in a fundamental way. Design efforts to cultivate intellectual potential and promote growth will ultimately demonstrate how nurture (with all its pedagogy, technology, and resources) can stretch the limits of human potential, and how nurture may be constrained by nature (Dai, 2010).

The Empirical Imperative

Whether design research is a viable method for generating theoretical as well as practical models of enhanced intellectual functioning and growth depends on whether "smart learning" indeed results from the design work. This is particularly true in the larger policy and funding context (Kelly, this volume). Finding proper ways of assessing the progressions in learning and thinking continues to be a main challenge. In that regard, technological breakthroughs in assessment of intellectual functioning in situ and growth over time in design research are critical in producing credible evidence, which can convince stakeholders of education and skeptics that a more ambitious education agenda aimed at high-end learning and higher-order thinking is indeed viable. In addition, design research aimed at promoting deep understanding and higher-order thinking has yet to confront evidence of individual differences in learning and thinking (Ceci & Papierno, 2005) head-on, rather than treating this body of literature as irrelevant. How individual participants differentially benefit from a particular design, and how a design is adaptive to individual difference constraints are also legitimate questions (Snow, 1992). Design research has to show that, while the more able may indeed gain more with education interventions (Ceci & Papierno, 2005), almost all students can gain intellectual grounds when instructional designs engage their agency and address their needs or particular constraints. Design research will also need to f[illegible]n a new language of interpreting data and making evidence-based claims, switching from simple, linear cause–effect mapping to more complex,

multi-level affordances–constraints, means–ends analysis. Validity needs to be redefined from the new epistemic stance in terms of whether insights gained from the research help bring about meaningful, positive changes (Barab et al., 2010). As a new methodology, design research is well poised to achieve both relevance and rigor; however, it is still in its early stage of development, and there are more questions than answers regarding its nature and efficacy. For example, just as a design study can be underconceptualized and overproceduralized, as Dede (2004) pointed out, it can also err on the opposite, overconceptualizing and underproceduralizing, falling short of operationalization and substantiation, with a design remaining "theoretical."

The Practical Imperative

Design research is normative, concerned with what "ought to be" (Simon, 1981). There is an inherent aspect of educational innovation in it. The past century has witnessed a sea change in social and economic development, facilitated by dazzling scientific and technological advances, yet the structure of schooling, as well as how curriculum is structured and delivered for the same period, remains virtually unchanged (Collins & Halverson, 2009). In the spirit of designing for a better future, design researchers should take on the challenge of designing learning environments for optimal development of the young generations. New conceptions of learning and instructional psychology that integrate learning, thinking, and development are just one way to meet the challenge of the new world, a global knowledge economy, which demands a workforce capable of making adaptive changes and productively using knowledge in problem solving and decision making, of capturing new opportunities and dealing with uncertainties in an ever-changing work environment and job market. The design research community ought to contribute its scholarship to the public discourse on competencies and skills needed for the new century (e.g., Partnership for 21st Century Skills, 2008). The topics of building deep conceptual knowledge, enhancing complex problem solving, critical thinking and creativity, of promoting self-direction and collaborative skills along with academic ones ought to be part of the research agenda for design researchers. When everything is said and done, it is the consequential validity that ultimately determines the viability and promise of design research.

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2

INTELLIGENT ACTION AS A SHARED ACCOMPLISHMENT

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Traditionally, intelligence has been thought of as an individual attribute that people carry across contexts. Both our measurements of intelligence (they take place outside of any familiar context of learning, using protocols that make assumptions about the separation of content and context) and the ways we talk about intelligence (someone *is* "smart" or "gifted," rather than someone might *act* smart) indicate our overwhelming belief that intelligence is ultimately a property of an individual. In this chapter, we propose a different vision of intelligence, one that focuses on how we learn to act in ways that are recognized as more or less intelligent, and the role of the environment in making an individual appear intelligent or not. Specifically, we propose a way of thinking about intelligence that highlights the kinds of *disposition* we develop to act in particular ways, and consider how those dispositions develop in relation to learning opportunities with which learners are presented over time.

We come at this issue from a relational ontology that makes particular assumptions about the location of knowledge and intelligence as a shared or distributed accomplishment rather than an individual one. In other words, we purport that what it means to act intelligently is spread across individuals (both the person acting intelligently and those others in the immediate context), and is inseparable from available tools (such as computers or dictionaries), norms and expectations (whether risk taking is supported or punished), opportunities for action (for example, procedural versus more conceptual expectations for action), and personal history (such as knowing how to understand a particular interface or participate in a particular context) to environmental particulars of the immediate situation. In this way, a relational ontology focuses attention on the individual-in-context, and how people use the world around them to scaffold their meaningful participation. It is according to this perspective, for example, that