A Conceptual Framework for the Development of Theories-in-Action with Open-Ended Learning Environments

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Open-ended learning involves learning processes that are mediated by the unique intentions and purposes of individuals. Open-ended learning environments (OELEs) have been touted to support the building and evolving processes associated with self-directed learning. OELEs provide technological tools and resources for manipulating and exploring concepts. Whereas previous research has provided descriptions of OELE designs and case studies, little insight exists as to the processes used by learners to build and evolve their understanding. This paper describes a rationale for, and conceptual framework of, learning via open-ended environments.

☐ **Recent technological developments have enabled researchers to explore the use of computers and related technologies to support a** variety of innovative teaching and learning approaches. Contemporary theoretical perspectives such as constructivism (Jonassen, 1991), situated cognition (Brown, Collins, & Duguid, 1989), and cognitive flexibility (Spiro, Feltovich, Jacobson, & Coulson, 1991) emphasize the centrality of the learner to understanding. Furthermore, the re-emergence of ideas first introduced by Vygotsky (1978) and Piaget (1970; 1976) has been linked with contemporary pedagogical approaches such as microworlds (Papert, 1993a; 1993b; Rieber, 1992) and anchored instruction (Cognition and Technology Group at Vanderbilt, 1992). The learner is viewed as an active constructor of knowledge; accordingly, a need for systems that empower learners through self-directed learning has emerged.

Open-ended learning environments (OELEs) have been touted as a contemporary student-centered learning approach (Hannafin, Hall, Land, & Hill, 1994). Open-ended learning involves activities that are mediated by the unique intentions and purposes of the individual (Roth & Roychoudhury, 1993). OELEs capitalize on technological capabilities to provide opportunities to represent and manipulate complex, and often abstract, concepts in tangible, concrete ways. The learner does not merely respond to the system; rather, he or she is integral to it. The individual determines what, when, and how learning will occur based on unique goals and needs that emerge while engaging the environment.

OELEs employ technology to enable learners to build and test their intuitive, and often misconceived, notions about the world. Research in science education, for example, has indicated that individuals develop informal theories about scientific phenomena, which may help or hinder their subsequent learning prior to formal instruction (Driver & Scanlon, 1988). These theories tend to be implicit and reflect the vast differences in the range of individual experience. For instance, young learners typically hold naive views about concepts such as force and motion, embracing an *impetus theory*—a misconstrued belief that an object continues to accelerate as the direct result of a stronger force acting upon it—to explain how objects move through space (Carey, 1986; Hawkins & Pea, 1987; Piaget, 1970; Twigger et al., 1991). Thus, children often believe that a ball may move simply because it has been kicked; they believe it moves faster when it is kicked harder. Such intuitive beliefs are strongly rooted in personal experience, but are often inconsistent with canonical explanations. This is due, in part, to a lack of experience with events that challenge one's intuitive understanding (Lee, Eichinger, Anderson, Berkheimer, & Blakeslee 1993; Vosniadou & Brewer, 1987). This provides a limited basis for conceptual understanding that, as a consequence, is often superficial, inert, and riddled with misconceptions (Carey 1986).

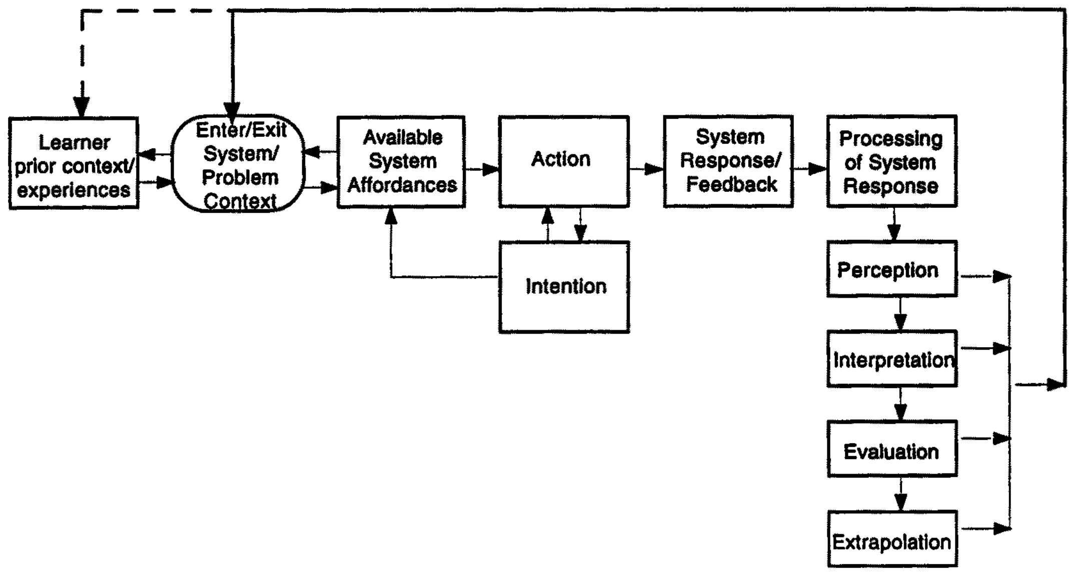
Theory-building is the process through which understanding evolves. OELEs support experiences wherein learners begin to explore, build upon, and make explicit their intuitive notions. OELEs often provide concrete, manipulable objects in order to support the initial transition from intuitive- to experienced-based understanding. Unobservable forces in physics, such as friction, mass, speed, and mechanical power, can be manipulated by learners to vary the parameters and note their physical consequence (Twigger et al., 1991). Through interaction, learners construct a "working model" that is progressively honed via the manipulation of OELE features. Through interaction, learners make their ideas explicit and clarify and extend both their understanding and implicit models (Driver & Scanlon, 1988)

OELEs assume that understanding is a continuous and dynamic process that evolves as a result of observation, reflection, and experimentation (Hannafin, 1993; Hannafin et al., 1994). OELEs support experiences for learners to identify, question, and test the limits of their intuitive beliefs. As such, learning involves developing a *theory-in-action*—an intuitive theory that is generated and modified as individuals reflect upon experiences that either confirm or challenge the validity of their theory (Karmiloff-Smith & Inhelder, 1975). However, little insight exists as to the processes through which learners dynamically construct and evolve intuitive theories using OELEs. This paper outlines an empirically- and theoretically-based model representing how learners build and evolve personally-derived theories-in-action via OELEs.

THE DEVELOPMENT OF THEORIES-IN-ACTION WITH OELES: A CONCEPTUAL MODEL

Figure 1 presents the proposed conceptual model to represent the theory-in-action development process. This section introduces the components of the model, as comprised of five primary elements: (1) learner and system context; (2) system affordances; (3) intention-action cycle; (4) system response/feedback; and (5) learner processing. Individuals engage the OELE's problem context, interpret the goals of the system, elaborate them based on personal knowledge and experience, and even redefine the system's goals (e.g., applying a system tool to perform calculations for a personal interest beyond the immediate environment). The individual then explores and refines a theory using the tools and resources afforded by the system. Affordances represent ways in which tools and resources of the system are *designed* to promote learning, not necessarily how they are actually *used*. At this stage, knowledge and experience are continually cross-referenced with the problem context to determine what action should be taken. Action may take the form of simple browsing, with little or no intent to test a theory, or be "thought-based" and mediated by the individual

Figure 1 □ Conceptual model for developing theory-in-action via OELEs.



intentions to test understanding. The system provides feedback, based on the actions of the individual, which are subsequently processed according to the individual's intentions. As intentions and actions are increasingly linked with the feedback and subsequent processing, the theory-in-action is examined critically. Problem contexts continue to evolve, and based upon deepened processing, intentions and actions become more calculated and differentiated. Over time, the theory-in-action evolves based upon progressively refined interactions in the OELE, which allow the individual to further speculate, test, and observe.

The Role of Context

Learner Background. Learners often lack formal domain knowledge, but they are *not* conceptually naive. They use extensive prior experiences and evolved beliefs to interpret their world at an intuitive level (Piaget, 1976). Learners possess a great deal of intuitive understanding and experience, but are often unaware of how they relate to formal domain knowledge.

According to Hannafin (1992), personal beliefs, experiences, and conceptual schemata support current, as well as provide the foundation for new, understanding. These background influences can be *explicit,* wherein learners intentionally reference related knowledge or experience based upon conscious perceptions of relevance, or *implicit* (tacit) for which learners have no conscious awareness (Edwards, 1995; Karmiloff-Smith & Inhelder, 1975). Learner background can take the form of preferred learning styles, interests, motivation, self-efficacy, goal-setting behavior, and strategies for decision-making and problem-solving. Background context influences the choices learners make in the environment, the extent to which they persevere on a task, and the types of goals they set (cf., Cervone & Wood, 1995).

Background knowledge and experience forms the conceptual referent within which new encounters are organized and assimilated (Piaget, 1976). Individuals with extensive related knowledge and experience will typically solve and generate problems much differently from those with limited related experience. Problem-solving research, for example, indicates that experts possess hierarchically-organized knowledge that is accessed quickly and efficiently (Mestre, Dufresne, Gerace, & Hardiman, 1993). Thus, experts rapidly reason through problems holistically, evaluating the most appropriate concepts and strategies for solving them. For instance, a seasoned engineer will draw upon a large subset of accessible experiences to engage scientific problems at a deeper level (cf., Chi, Glaser, & Rees, 1982). A novice student, on the other hand, has limited relevant first-hand experiences, providing few referents for developing workable problems and solutions. Unlike the expert, the novice's approaches typically focus on surface aspects of a problem, such as the procedural application of formulas and equations. Whereas the engineer already has a foundation of related physics knowledge and experience, it is assumed that the novice will use an OELE to establish and progressively refine intuitive understanding.

Yet, while links to prior knowledge enhance the potential for transfer (Brown et al., 1989), they often reference incomplete and inaccurate understanding which underlie faulty theories. For instance, while learning physics by using a roller-coaster simulation, one learner recalled a roller coaster operator stating that roller coasters were equipped with brakes. As a result, she often attributed slowing down to her belief that the coaster's brakes were used even though brakes were unavailable in the microworld. In this case, legitimate prior experience confounded interpretations when manipulating force and motion (Land, 1995). While the potential benefits of building upon personal experiences are clear, the risks can also be considerable.

In most conventional teaching-learning approaches, learners have little control over what (or how) they are taught. Learners often try to adjust their thinking to comply with perceived expectations of others, such as teachers (McCaslin & Good, 1992), thereby limiting the potential of OELEs to support student-centered understanding. Learners may seek answers or explicit criteria for success that are unavailable in open learning environments. With OELEs, learners must generate meaning; instructors or tutorials are not available to "tell" learners how to interpret events (Hannafin et al., 1994).

OELEs require sophisticated individual management and evaluation of one's learning process. Learners must be "mental managers" of the learning *process*—they must choose relevant activities, interpret results of activities, and evaluate the fruitfulness of their approaches (Perkins, 1993). Furthermore, learners must utilize strategies—both cognitive and metacognitive—in order to manage and organize their understanding.

Learners must also apply cognitive strategies to plan for problem-solving and decision-making. Cognitive strategy decisions involve *when* to take *what* actions (Perkins, 1993). In physics, for instance, many children establish intuitive cause-effect relationships between the weight of an object and its buoyancy: heavy objects sink while light objects float. They do not yet understand the influence of more abstract principles, such as the influence of density on buoyancy, but have experience with floating objects in pools, rivers, and ponds. Consequently, if an object sinks, learners would likely attempt to reduce its weight, reflecting tacit beliefs derived through everyday experience. Others, however, might strategically maintain a constant weight while varying a different factor (e.g., surface area) to see if the object will float. If the object floats, new data have been generated which require reflection. Through systematic exploration of the boundaries of known relationships, OELEs allow learners to encounter experiences that can subsequently extend or modify understanding.

To be effective during open-ended learning, learners must also monitor their thoughts and actions. Learners interact based upon metacognitive awareness of their understanding and the perceived need to validate or challenge their understanding (Perkins, 1993). This includes decisions to pursue additional practice, search for definitions or information, test a hypothesis, create a "what if" scenario, or take notes. Learners evaluate their need to know and perceive limitations in their understanding which become the bases for subsequent actions. Effective library research, for example, requires metacognitive knowledge as well as awareness of the corresponding retrieval resources (Moore, 1995). Learners must be able to locate, select, organize, integrate, and use relevant information. Similarly, learners must evaluate the adequacy of their approaches during open-ended learning (Belmont, 1989). This is especially important given the numerous learner control studies which suggest learners often fail to both invoke self-regulation strategies and initiate and direct their own efforts (Steinberg, 1989; Zimmerman, 1989).

In sum, OELEs support student-centered learning processes reflecting the purposes, intents, and background experiences of individual learners. Rather than providing direct instruction to transmit formal concepts and knowledge, OELEs provide contextually-based and experientially-rich opportunities to engage formal concepts. Learners begin to develop formal understanding as they apply everyday knowledge to solve and generate problems. OELEs provide a transitional system (Papert, 1993a; 1993b) to help connect informal knowledge and experience with formal knowledge domains and concepts. In order to benefit from OELEs, however, learners must access prior experiences, make sense of new experiences, and evaluate their own learning approaches and needs.

Problem Context. The problem context influences how individuals make decisions, activate prior knowledge, and take responsibility during the learning process. Learners reference their background and experience, and engage learning based on the problems posed by the system. In the *Jasper Woodbury Series* (Cognition and Technology Group at Vanderbilt, 1992), learners attempt to transport a wounded eagle to a nearby facility. They must evaluate the distance to be traveled, the alternatives available for travel (hiking out, ultralight airplane, etc.), and the problem constraints (fuel requirements, weight limits for ultralight etc.). Learners make decisions, investigate possibilities, and generate and solve subproblems using data embedded within the problem scenario. The environment establishes a context for identifying unmet learning or information needs, accessing prior experiences, and generating plausible strategies and solutions.

OELEs often provide orienting scenarios to guide learners in exploring the complexities of a problem (Hannafin et al., 1994). For instance, the *Science Vision* series (see Tobin & Dawson, 1992) encourages exploration of scientific concepts within student-centered problem contexts. The problems are defined during brief orienting movies that introduce a challenge facing the student team. Orienting scenarios often focus on everyday problems such as environmental pollution and the contamination of drinking water. Learners explore problems by collecting water samples at various points along the river, conducting laboratory analysis of the samples, consulting on-line experts, and referring to other available resources such as on-line periodic tables. These scenarios set the boundaries for system use and establish a framework for learners to generate and solve new problems. Thus, learner actions are influenced not only by personally-held goals and beliefs, but also by the problems, activities, and information introduced by the system.

Thinking processes and the contexts in which they occur are inextricably situated, that is, they cannot be separated from their experiential referents (Brown et al., 1989; Perkins & Salomon, 1989). This assumption is the basis for the "everyday problem" scaffolding frequently provided in OELEs. OELEs provide familiar, authentic contexts to facilitate the linking of new concepts with prior knowledge. For instance, learners might learn about the concepts of buoyancy and water displacement using the everyday context of a swimming pool, a familiar referent for students. Once confronted with a problem, learners apply their experiences, as well as conceptually similar experiences (e.g., submerging a cup into a basin full of water), to organize and interpret new information. Learning via OELEs is facilitated when opportunities to connect prior and everyday knowledge to the problem contexts are provided (Choi & Hannafin, 1995), allowing the learner to reference new experiences to prior knowledge and intuitive understanding.

System Affordances: Tools and Resources. Pea (1993) refers to affordances as ". . . perceived and actual properties of a thing, primarily those functional properties that determine just how the thing could possibly be used" (p. 51). OELE affordances include a variety of tools and resources that facilitate learner use and understanding of the embedded concepts. The implementation of tools and resources is critical. For instance, computer graphing tools typically allow learners to illustrate visually two-dimensional relationships. These tools provide an *opportunity* to engage in higher-order thinking, but do not inherently enhance cognitive activity or skills. However, tools and resources may also alter thinking and require very different cognitive processes. Graphing tools can deepen thinking by allowing learners to develop and test hypothesized relationships among variables, such as the influence of varied headwind on aircraft with different drag coefficients. Regardless of the apparent power of tools and resources afforded by OELEs, it is unlikely that learners will be spontaneously mindful without thoughtful facilitation.

Tools provide the means to create and manipulate models of understanding, as well as to monitor ongoing knowledge construction processes. Computerized tools can be used to select text for electronic notebooks, create hyperlinks between sources of information, perform calculations, input data for graphical or tabular representation, or select objects for manipulation (Hannafin, 1992). Microworld tools, such as *Geometer's Sketchpad*™ and *Geometric Supposer*™, allow learners to construct geometric objects, as well as to rotate, slide, and flip them. Thus, learners use tools to construct and manipulate physical models based upon their evolving understanding (Edwards, 1995; Lewis, Stern, & Linn, 1993). Technological tools, in this instance, alter both the experiences available to learners and the cognitive requirements of the learning task (Salomon, 1986).

OELEs often provide interactive multimedia resources through which learners access information. They then construct artifacts of their understanding using the available tools. For example, learners can explore rich multimedia, the outcome of which can be represented as a product (e.g., a concept map, a multimedia presentation, a plan or design, or a research paper). Some environments also provide tools that facilitate the *construction* of resources by learners, versus simply the provision of access to static resources. In research reported by Harel and Papert (1991), students learned about fractions by designing and constructing educational software for teaching younger children about fractions. In effect, an artifact of individual understanding (i.e., software about fractions) becomes a resource to others.

Tools can augment or supplant cognitive processes, depending on the extent to which they deepen or extend the learner's processing activity (Hannafin, 1992; Papert, 1993a; Salomon, 1986). Ideally, learning environments provide resources and tools that engender higher-order conceptual thinking and understanding, rather than "short-circuiting" learning. In a previous example, the spreadsheet was used to support what-if thinking by enabling the testing of various combinations of headwind speed and aircraft design. The tool was used by learners to test complex theoretical concepts in concrete ways. In contrast, many systems generate solutions, but fail to make the underlying principles accessible to the learner. An expert system, for example, may prompt learners to provide the color, hardness, and transparency of a mineral in order to determine its identity. The system can subsequently identify the mineral based on the information entered and rules, but provides neither the means to understand the underlying rules nor the heuristics which must be understood in the absence of the system (Salomon, Perkins, & Globerson, 1991). In OELEs, affordances support and extend the zone of proximal development, enabling learners to explore concepts in ways that minimize the problems associated with irrelevant or tedious performance requirements (Salomon, Globerson, & Guterman, 1989).

Available tools and resources may fail to promote understanding *if* the OELE does not facilitate the needed cognitive or conceptual processes. Recent efforts have emphasized activities that induce and facilitate high-level cognitive processes, such as hypothesis generation, scientific reasoning, or metacognitive analysis. For instance, *CSILE* (Computer-Supported Intentional Learning Environment) is designed to facilitate metacognitive thinking through the use of prompts to generate questions, hypotheses, or theories (Scardamalia, Bereiter, McLean, Swallow, & Woodruff, 1989). The system encourages awareness of normally tacit metacognitive processes through electronically-facilitated intentional reflection, dialogue, and collaboration. Other environments facilitate scientific inquiry by embedding activities that induce learner hypotheses and observations prior to data manipulation and collection (see for example, Lewis et al., 1993), and enable learners to experiment with their intuitive experiences by constructing and testing physical models (Twigger et al., 1991). Environments designed to invoke conceptual, strategic, and evaluative processes are more likely to prove successful when facilitation is provided for the use of available tools, activities, and resources.

Intention-Action Cycle

The evolution of understanding is not an isolated activity that occurs solely in the minds of individuals. Understanding is manifest ". . . in activity that connects means and ends through achievements" (Pea, 1993, p. 50). Thus, in order to perceive and test the limits of understanding, learners act to test their theories. The tools and resources that support action serve as a link between how concepts and knowledge are represented in the system, and how learners act to establish and refine their conceptual understanding (Driver & Scanlon, 1988).

Schön (1983) used the term *reflection-in-action* to describe the process of thought-based action. Thinking is not separated from doing; they are complementary. In reflection-in-action, intuitive understanding becomes overt and, as a result, becomes amenable to experimentation and scrutiny. Schön described the connection:

> Doing extends thinking in the tests . . . of experimental action, and reflection feeds on doing and its results. Each feeds the other, and each sets boundaries for the other. It is the surprising result of action that triggers reflection, and it is the production of a satisfactory move that brings reflection temporarily to a close . . . Continuity of inquiry entails a continual interweaving of thinking and doing. (p. 280)

Reflection-in-action, then, links a learner's actions toward a goal with his or her thoughts about the consequences or feedback associated with actions. Some actions yield an anticipated result, and merely strengthen one's beliefs. Unanticipated results, on the other hand, may trigger a learner's reflective processes in an attempt to reconcile the unexpected event. Once initiated, reflection becomes linked with action; actions, in turn, become increasingly reason-based.

Not all actions, however, are the product of deep reflection and reasoned intent. OELEs are susceptible to non-strategic, unsystematic, and trial-and-error approaches. Frequently, learners fail to clarify their intent prior to responding, or do not recognize the relevance of available information to their intentions. In a study reported by Atkins and Blissett (1992), for example, learners were asked to "crack" a code by entering numbers and receiving feedback as to the numbers that were correct. It was expected that learners would use the information from previous trials, and apply known statistics concepts, to guide their intent and actions. Instead, they often used random, trial and error approaches until they eventually solved the problem. Similar observations were reported by Hill (1995) and Land (1995), each of whom observed frequent failures to establish or alter intentions and actions, despite the availability of task-relevant information.

System Response/Feedback

In OELEs, feedback assumes many forms. Unlike conventional approaches, feedback involves more than confirmation of the accuracy of a response. Feedback in OELEs is the system's response to any learner action, including tool manipulations, resource utilization, and requests for guidance. OELE systems may respond using visual, verbal, tactile, or combined images (Hannafin, Hannafin, & Dalton, 1993). Feedback images may be related to the problem itself (consequences of action, depiction of an evolution in the problem context, information sought from resources), to the strategies used by the learner (diagnostic-prescriptive advice, updates on performance, guidance as to alternative approaches), or to personalize the context (motivational, vivid, relating problem to the learner's experiences). Through feedback, learners re-evaluate their beliefs, explore alternative explanations, and revise understanding (Edwards, 1995; Piaget, 1976).

System feedback further facilitates the connections among learner actions, intentions, and underlying theories. Formative theories are tested as learners take action and collect data in the form of feedback. For example, the effects of the relative angle of the earth to the sun on seasonal changes can be examined interactively by changing the angle of the Earth's axis. An action (e.g., setting the Earth's axis to zero degrees) produces a result which is represented via system feedback. Learners observe and process this feedback; the cycle continues as learners evolve their theories by establishing intent, taking action, and examining system feedback.

Feedback is characteristically linked to varied representations, often linking a symbolic system (e.g., Logo commands, object manipulation) with verbal responses (e.g., textual or aural information requested via a system resource), visual representations (e.g., a video or graphical display of an action generated via a tool), or sensory-tactile feedback (e.g., centrifugal force generated in space shuttle simulators) (cf., Edwards, 1995). The opportunity to test assumptions, as well as to receive feedback related to learner actions, is critical to understanding.

If learners fail to relate feedback to their theories, they may not perceive how data support, or contradict, their beliefs. For instance, in the buoyancy example, many young learners evolve the rigid belief that all metal objects sink, while all wooden objects float. These tacit principles are so consistently reinforced through personal experience that they become the foundation of firmly-established, though often fundamentally flawed, theories. In some cases, underlying beliefs are so entrenched that learners fail to consider testing them. Even in cases where contradictory feedback is provided (i.e., tin cans float, ebony sinks), learners fail to relate the feedback to their theory and challenge their assumptions (i.e., density also influences whether or not an object floats).

Because they evolve from individual experience, personal theories are often highly resistant to change. Faulty and incomplete intuitive beliefs may actually strengthen in the face of contradictory evidence. Owing to subjective perceptions of data, beliefs are often confirmed despite feedback that is inconsistent with the theory. In effect, contradictory data are adapted to fit an existing theory, rather than used to re-assess the theory (Land, 1995). Consistent with research in response and acquisition bias (Wilson & Brekke, 1994), individuals often "protect" their underlying beliefs, rendering feedback of limited value in altering underlying beliefs and theories.

In sum, OELEs provide a variety of tools, resources, and system feedback to help learners to generate, test, and evolve personal theories of understanding. The mere provision of tools, resources, and feedback, however, does not inherently induce thought-based action and theory development. Learners must think and act with intention to generate and solve problems, test ideas, and seek objective feedback related to their theories. Some learners meet the cognitive and metacognitive demands of open-ended learning; many others, however, do not. OELEs must intentionally facilitate on-going learner needs, reflection, and interpretation.

Levels of Processing

The processing associated with thought-based action, and the corresponding capacity to evolve personal theories, are hierarchically linked and interdependent. Our conceptual model reflects four levels: perception, interpretation, evaluation, and extrapolation. As cognitive processing is deepened, theories-in-action become more sophisticated, refined, and amenable to scrutiny.

Perception. According to the model, processes initially become linked with action when learners perceive the cause (action) of an event (feedback) and formulate an intention to act accordingly. Without perception of cause-effect, actions fail to elicit deeper cognitive processes, and theories fail to evolve. Initial theory development relies on perceiving actions that are associated with goal attainment (e.g., vary parameters such as weight, density, and volume to make an object float vs. sink).

While perceiving, learners may "explore for exploration's sake" in order to narrow their actions to those deemed most relevant for attaining their goals (Karmiloff-Smith & Inhelder, 1975). Through the goal-setting process (e.g., wanting to see how heavy an object can be before it sinks) and perceiving the consequences of actions (e.g., observing when the object sinks), learners collect data on actions associated with success. As a result, they begin to catalogue actions that have proven consistently successful. During initial perception, learner attention is focused on selecting information (conceptual, affective, visual, auditory) used to meet goals (Mayer, 1989). Learners do not yet access personal knowledge to explain events or feedback; rather they build and refine simple cause-effect relationships that will subsequently be used to interpret events.

Perception is evident as learners link their actions with the system's feedback (Chan, Burtis, Scardamalia, & Bereiter, 1992; Karmiloff-Smith & Inhelder, 1975). Examples of perception include simple reporting of actions and events (e.g., observing the results of a simulation), restating what was heard, and reporting visual feedback associated with success or failure (e.g., observing the density of a metal ball and the weight of the water displaced before it sinks). Perception involves a recognition or reporting of events, effects of actions, or information relevant to a goal, but does not involve inference or interpretation of meaning.

In order for theories-in-action to develop, learners must recognize and label system events (e.g., an object sank), determine the effects of their actions (e.g., when I increased the density, the object sank), sort relevant from irrelevant information, and interpret according to their beliefs (Land, 1995). The initial and ongoing perception of relevant information is critical to theory development in that it aids establishing cause-effect relationships between what is observed and one's understanding.

Interpretation. Intention-action-feedback associations are the basis of interpretation. Interpretation involves coherent or meaningful organization of conceptual, logical, or sequential relations among the variables contained in a system (Mayer, 1989). Learners offer interpretations to explain regularities in perceived data or deviations from previously-held expectations (cf., Karmiloff-Smith & Inhelder, 1975). As interpretations evolve, learners generalize prior or everyday experience to explain system concepts, indicating that a theory-in-action, implicit or intuitive, has been constructed which is used to interpret cause-effect events in the environment (Land, 1995).

With OELEs, interpretations may be evident in learner descriptions of how variables or ideas are related. In thermodynamics, a learner may observe that a given insulation material slows the cooling process of an object, and offer a simple explanation for it. These explanations may reflect naive understanding, but they enable personally meaningful interpretation. For instance, when learning how objects float or sink in the context of a swimming pool, a young learner might state: "Metal objects can't float because pennies always sink to the bottom of the pool, but plastic rafts always float." Personal knowledge is referenced to explain a system event, even though the interpretation may be faulty.

When learners initially use an OELE, they may be unable to establish links between their personal experiences and the formal concepts represented in the system; or, as noted previously, their experience may provide only introductory scaffolding for richer, more abstract, conceptual understanding. They may derive simple cause-effect relationships that focus on specific rules, which are strengthened or weakened depending on whether they reliably predict success or failure (Hawkins & Pea, 1987; Holland, Holyoak, Nisbett, & Thargard, 1986). As learners refine and expand their rule sets, they develop conditional expectations or predictions regarding future success (e.g., "if density is high, the metal ball will sink"). When expectations or beliefs are not met (e.g., a plastic object with a high density sinks), dissonance results and learners attempt alternative interpretations (Karmiloff-Smith & Inhelder, 1975). Learners may continue to reference prior experiences to explain the event, but they do not yet possess sufficiently complete personal theories such as those of an expert. Rather, they attempt to formalize and elaborate their intuitive beliefs through the OELE.

Evaluation. Once learners have interpreted responses according to their implicit theory, explorations become more systematic. They use the theory as the basis for predicting events (Chan et al., 1992). For instance, once a theory is tendered related to the influence of density on an object's buoyancy, learners act to test it (e.g., decrease density if it sinks, increase density if it floats). They use new data derived from system feedback to confirm or refute their theory. Karmiloff-Smith and Inhelder (1975) refer to such evaluations as *theory responses* because learners evaluate whether their theory is consistent or at odds with system feedback. Learners can evaluate their understanding only after they have formalized an initial theory. Once the theory is formalized, learners can evaluate events that are dissonant with the theory, thus recognizing instances that are counter to it.

Because of the persistence of tacit theories-in-action, learners must encounter repeated feedback which challenges the adequacy of their theory. Learners initially try to assimilate or attach the conflicting information into the existing theory (Piaget, 1976). For instance, if confronted with conflicting data about the validity of a personal theory about how objects float (i.e., a ball continues to sink even when density is decreased), learners might attempt to assimilate the feedback by offering a conditional statement or *exception rule* (e.g., the shape of the object must also be affecting it) in order to preserve the underlying theory (Holland et al., 1986). The goal is for learners to generate unifying principles to explain phenomena, rather than to construct situational exceptions independent of their theory. The evaluation of deep-rooted intuitive theories requires both time and intentional reflection on both thoughts and actions.

Reliance on traditional instructional approaches may limit the extent to which learners can engage in complex ideas (Spiro et al, 1991). Knowledge is neither inherently hierarchical nor the incremental product of teaching methods, but a natural consequence of curiosity, experience, and insight. Learning is best achieved through extended investigation and experience with the phenomena under study (Papert, 1993a; 1993b). Understanding involves continually modifying, updating, and assimilating new with existing knowledge. Understanding results from the continuous testing of beliefs and fforts to reconcile them in the face of ever-changing experience. OELEs capitalize on the dynamic nature of knowledge by providing means for developing, testing, and refining personal theories. The goal, then, is to bring learners into contact with new knowledge and experience, wherein they can deploy diverse, personal knowledge and use tools with which to augment and extend their thinking.

Extrapolation. Once learners have evaluated limitations in their theory, they extrapolate information from the system and their current understanding to accommodate the new information (Piaget, 1976). When learners adopt a more encompassing theory, they are able to modify their understanding and generate new problems. The process is considered complete when learners respond adaptively in the environment and infer newly developed principles in novel situations (Spiro et al., 1991).

Given repeated opportunities to test objects of varied density in the buoyancy problem, learners eventually question how different liquids influence buoyancy. They may, for example, recall a television program wherein objects seemingly never sink in the Great Salt Lake.

Through OELE manipulation, they can test a formative theory that the density of the liquid also affects the buoyancy of an object. They observe that many objects that float in water are not buoyant in gasoline, and that many objects that sink in distilled water now float in salt water. They may extend their theory to account for buoyancy as a function of the relative density of two substances rather than focusing solely on the isolated properties of one. In effect, the sophistication of the resulting theory transcends the limits of the system affordances.

With OELEs, extrapolation also involves extending ideas beyond the scope of the immediate problem context. Extrapolation is marked by a connection of both personalized knowledge (or context-independent knowledge) and newly acquired, context-specific knowledge (Chan et al., 1992). Extrapolation may be indicated by a need or desire to (a) explain different problems with the same ideas or concepts; (b) use different concepts or perspectives to explain the same problem; or (c) find a new framework to accommodate conflicting data.

Analog problems (Cognition and Technology Group at Vanderbilt, 1992) are useful in demonstrating how principles and experiences can be extrapolated from one context to another. Alternative (or analog) perspectives are useful for enhancing transfer and enriching theory flexibility (Language Development and Hypermedia Research Group, 1992; Spiro et al., 1991). In a physics microworld, learners can manipulate parameters of a roller coaster such as hill size, mass, curve radius and engine horsepower (Tobin & Dawson, 1992). An analog problem might involve the manipulation of additional variables such as friction levels and curve banking, or extend the context in which the concepts are embedded (e.g., learning about the physics of racetracks, speedboats, or sports motion). As learners become increasingly flexible in using the environment, they extrapolate familiar metaphors, parallels, or analogies from prior knowledge to establish, elaborate, and refine experienced-based theories. Learners begin to generate problems that are driven by experimentation of their *own* ideas versus those supplied within the OELE.

Summary of the Conceptual Model

This paper offers a rationale and framework related to how learners develop theories-in-action with OELEs. The conceptual framework is based on assumptions about how learners process information, use prior experiences, and formulate reasons and strategies for action. The structure and design of the environment can be optimized by addressing the cognitive requirements of theory development, as outlined in the conceptual model. The process of theory development is not likely take place spontaneously without facilitation; instead, problems, tools, resources, and feedback must increase the likelihood that learners will both formulate initial theories and subsequently evolve them.

In order to evolve a theory-in-action, a set of initial premises must first exist. The experience and knowledge of the individual, in effect, establish a personal context through which the problems, affordances, and feedback are filtered, analyzed, and processed. Given even limited related background, intuitive models can be initially constructed and subsequently tested. Learners use these intuitive models to explain the events they encounter, and cause, as they interact within the OELE. Their initial models may be simplistic or naive, but they permit progressive refinement through manipulation.

Using a theory-in-action, learners act, perceive, interpret, and evaluate system-generated feedback to refine their understanding and evolve their theories. Theories evolve as learners encounter confirmation, counter-examples, or challenges prompting them to evaluate the legitimacy of their theories. However, contradictory evidence, alone, is often insufficient to change beliefs (Land, 1995; Vosniadou, 1992). Learners initially reconcile unanticipated evidence by adapting it to, or assimilating it within, their current beliefs. Learners may confront their beliefs through contradictory evidence, but tend to retain their current theory until powerful, repeated conflicting experiences cause them to revise it.

Theory evolution is further induced by linking learner intentions and actions. This strategy is essential for comparing new data with existing theories or data: Learners use the new data to elaborate their existing theory or generate a new one. Over time, learners evaluate data that are consistent or inconsistent with their theory (Piaget, 1976). When limitations in a theory are recognized, OELE affordances can be used with greater intention (Ackermann, 1991; Piaget, 1976). Theories-in-action evolve as learners derive alternative explanations and models consistent with scientifically accepted views (Vosniadou, 1992).

THEORY-BUILDING VIA OELES: AN EXAMPLE

The purpose of this section is to provide an empirically-based example of the theory development process. Land (1995) examined the theory-in-action development of middle school children using *ErgoMotion*, an interactive OELE within the *Science Vision* series, designed to encourage the manipulation of physical science concepts such as force and motion (see Tobin & Dawson, 1992). Learners are challenged to design a roller coaster—a familiar referent to students—by manipulating a variety of affordances within the environment. They do so in a microworld where they control a range of parameters such as hill size, curve radius, engine horsepower, and car mass to address varied challenges such as keeping the coaster on the track. Feedback is represented using video footage showing a coaster crashing, working successfully, or failing to ascend hills as intended. *ErgoMotion* also poses increasingly challenging problems, such as stopping the coaster at the top of a particular hill, or coming to rest in a valley between specified hills. Learners of varied background and experience engage the problem context with the challenge of designing a roller coaster that is both thrilling and safe.

Learners use the system resources (e.g., online experts and a video encyclopedia) and manipulation tools (coaster design site, presentation maker) to gather needed information as well as to represent and test a working model of their understanding. According to the model in Figure 1, learners use their prior background experiences as the anchor for generating and elaborating meaning in an OELE. They reference their informal, intuitive, and background experiences, both those directly involved in riding roller coasters and those derived from related experiences (e.g., riding around turns in automobiles, riding bicycles on hilly terrain) as the basis for making sense of the environment. To illustrate, during early interactions with the *ErgoMotion* environment, learners attempted to increase or decrease the speed of the roller coaster mainly by varying engine horsepower. Learners believed they could increase the speed of the roller coaster by increasing horsepower, and vice versa—a conception consistent with impetus theory. As they designed and tested a series of simulations, they received feedback indicating the effect of increased horsepower on acceleration. In this case, their prior conception (the impetus theory) was used as the organizing initial framework for interpreting system events.

System affordances were also deployed to accomplish individual goals and enable individual strategies. Through experience, learners became increasingly facile in the use of available learning tools and resources and developed an improved sense of how and when they could be used. For instance, one "bottom-up" learner decided that she needed additional information about *g-force* in order to construct a functional roller coaster. She recognized system resources (on-line consultants and video encyclopedia) that provide the data needed to accomplish her goal, and obtained input extensively prior to engaging the design challenge. In contrast, "top-down" learners often decided to immediately generate and test a hypothesis using the roller-coaster microworld. Actions are differentiated based on individual styles, goals, and intentions.

Learners also used system affordances to guide their decision-making. They changed, or developed, new intentions and strategies once they determined how features could be of greatest personal use. For instance, one learner discovered that he could manipulate friction levels in addition to hill size. Once this resource was understood, he pursued information about friction from on-line experts and eventually solved the problem. Thus, system features not only aided in operationalizing action for a given goal or decision, they also influenced how problems and strategies were conceptualized.

In some cases, learners generate goals that are not supported by the available tools and resources. For instance, one may desire additional explanations, or seek advice or information, beyond those afforded in the system. In such cases, the learners may try unsuccessfully to locate desired information or to deploy tools unavailable in the system. The inability of the system to accommodate such intents and goals may lead learners to devalue an otherwise valid strategy, reasoning that since the means are unavailable, the approach must be inappropriate. On the other hand, some might perceive that the system *cannot* provide the means needed to meet a goal, when the means are indeed available. This is evident in situations where learners fail to recognize that relevant information is available or are unaware of how to access it. One child searched for information about the motor size of the coaster to solve a problem. The information was not displayed at that moment, but was nonetheless available using a different feature of the system. In this case, the system provided neither the information the learner sought nor guidance in system use needed to address the questions. In order to build understanding, it is essential that the system facilitate learner use of available features.

Students process feedback resulting from their actions at various levels. During initial phases, perception and interpretation of system feedback helped to establish fundamental cause-effect relationships (e.g., "when I set the curve size to small, the coaster crashed"). Learners progressively refined these perceptions and interpretations until they connected their theories with observations (e.g., "the coaster crashed around the curve because the engine horsepower is causing too much speed"). They strengthened and formalized their initial theories by elaborating or revising them based upon system-generated feedback, prior experiences and knowledge, and intuition. For instance, in response to a roller coaster crashing around a curve in *ErgoMotion*, one learner attributed the cause as "too much speed" and elaborated it by recalling how automobile drivers apply brakes to slow down and negotiate curves. Such a learner may subsequently attempt to slow the roller coaster by lowering the engine's horsepower, believing that it will decrease speed of the coaster—much like the car when applying the brakes.

In some cases, the anticipated events are produced, reinforcing the assumptions of learner models; in other cases, expected events may fail to materialize. For instance, learners may expect the coaster to crash when negotiating tight curves because prior experiences with the system indicated this to be true. Likewise, they might formulate this expectation based on personal experience riding a bicycle around tight curves. Consequently, learners may be surprised to find that the coaster can also crash while negotiating a *large* curve, and under certain circumstances, negotiate the *small* curve successfully. Surprising or unanticipated consequences prompt learners to seek or generate explanations for the event from available resources or manipulation tools. Thus, feedback is interpreted and evaluated according to the individual's theory, which is further refined through subsequent actions to access resources or manipulate variables contained in the model. The cycle continues as personal theories are progressively elaborated using thought-based action and system feedback.

Once learners have established an initial theory based in personal understanding, they are able to evaluate the consistency-inconsistency of feedback with their theory. Once dissonance occurs, learners may evaluate and revise their theory. Karmiloff-Smith and Inhelder (1975, p. 209) note the result:

> Generalized application of a theory will ultimately lead to discoveries which in turn serve to create new or broader theories. However, it seems possible for the child to experience surprise and question his theory only if the prediction he makes emanates from an already powerful theory expressed in action.

As learners deepen their understanding, their theory-in-action becomes increasingly refined. New feedback is perceived and interpreted, theories are elaborated, and new data are assimilated. Learners become increasingly able to recognize limitations in their theories, and derive alternative explanations and models.

IMPLICATIONS FOR RESEARCH AND PRACTICE

The processes through which learners evolve their understanding provide significant opportunities for future research. It may be beneficial to examine and adapt methods used in other fields to better understand techniques for studying and influencing conceptual development. For instance, counseling psychologists employ reflective techniques and structured exercises to foster awareness of underlying beliefs (Rogers, 1961). Similarly, developmental psychologists examine stages of cognitive development as children mature from pre-operational to formalized thought (Piaget, 1976). Anthropological methods used to study cultural-historical development could be useful for studying how thinking evolves (Cole & Engeström, 1993). A further investigation of cognitive psychology in areas of mental model building, rule derivation and competition, and cognitive restructuring (Holland, et al., 1986) might also be useful for better understanding conceptual and cognitive development.

Another avenue for research involves how theory building and evolving are facilitated or hindered through social facilitation. Cooperative groups, for example, are assumed to promote sharing and the development of understanding (Johnson, Maruyama, Johnson, Nelson, & Skon, 1981; Palincsar & Brown, 1984). It is possible that cooperative encounters would be useful in challenging personally-held beliefs and making alternative theories and models available. However, it is also possible that cooperative groups might short-circuit awareness of beliefs on an individual basis. Individual learners might adopt strategies, processes, and actions of the group without addressing and refining their own beliefs. Further research into the ways that cooperative groups support the development, recognition, and evolution of theories is warranted.

Another recommendation for future research relates to the design of authentic contexts to support learners in linking prior with system-based experiences. Previous research indicates that learners experience difficulty connecting scientific concepts with their related prior knowledge (Carey, 1986; Hawkins & Pea, 1987; Land, 1995). Furthermore, when connections are made, they are often ill-informed or misconceived. The issue for researchers and designers becomes one of determining how to use OELE features to enable the linking of system actions with learners' prior experiences.

In order for OELEs to support theory development effectively, systems are needed that facilitate intentional reflection on, and evolution of, personal beliefs (Hawkins & Pea, 1987; Scardamalia et al., 1989). A lack of processing awareness leads to difficulties in recognizing counter-examples and detecting bias in thinking (Karmiloff-Smith & Inhelder, 1975; Wilson & Brekke, 1994). OELEs are designed to provide opportunities for intentional reflection on beliefs, strategies, and intentions. Several OELEs have been designed to facilitate awareness of beliefs with opportunities for metacognitive reflection (Scardamalia et al., 1989), identify observations, and develop hypotheses (Lewis et al., 1993). Further study on the effects of these tools on reflection and theory development is warranted.

As interest in OELEs continues to grow, it becomes important to explore issues related to implementation and practice. In recent years, many open-ended systems, such as the World Wide Web, have grown in use and availability (Shotsberger, 1996). It is now commonplace for many students, as well as professionals, to incorporate the World Wide Web into their daily practice. New approaches for helping individuals access available information, as well as to evaluate and learn from, vast, open-ended resources, are needed. Schools and organizations are recognizing the importance of developing independent, self-sufficient learners. Insight into the process and requirements of open-ended learning will help to establish effective contexts for and ways to invoke self-sufficient and self-regulated learning.

As OELEs are implemented in practice, a myriad of surrounding issues unfold. The more open the environment, the more complex the planning, management, and evaluation of it. Presently, outcomes and classroom activities are largely defined by existing curricula. One of the challenges for OELE implementation is to orchestrate on-going learning needs, resources, and desired learning outcomes that are not easily structured or predictable. In order to promote effective OELE practice, alternative methods for facilitating, managing, and evaluating student-centered learning are needed.

OELE implementation in classroom contexts produces questions regarding accountability and evaluation of learning outcomes. Traditional practices break content and information into identifiable skills that can be objectively evaluated. OELEs, however, are designed to promote learning *processes,* for instance, learning about the process of scientific inquiry or historical analysis, instead of applying equations or recalling factual information routinely. Scientists, for example, rarely engage in scientific inquiry through formalized instruction or methods. Instead, they engage in exploration and "getting to know" a concept through extended experimentation and revision of beliefs (Papert, 1993a).

While OELEs may not be the system of choice for all outcomes, they may, however, be more effective for addressing hard-to-teach problems such as critical thinking, scientific inquiry, and problem-solving. OELEs are designed to promote exploration and experimentation in ways that capitalize on the unique sense-making capabilities of individuals. The potential value of OELEs lies in their ability to support the kinds of learning that are often difficult to promote in traditional contexts. Many concepts, when taught via traditional instruction, are subject to misconceptions because of their abstract or counter-intuitive nature. Often, learners can objectively demonstrate mastery of skills, yet remain fundamentally naive in their *understanding* of mathematical or scientific concepts (Perkins & Simmons, 1988). OELEs are designed to support learners in extending the boundaries of what is known with opportunities for reflection, concrete manipulation, and experimentation. With OELEs, learners can easily explore the effects of varying parameters not typically possible—objects in a gravity-free world, temperature levels that can exceed thousands of degrees, or functions and manipulations of the human brain. While questions remain regarding effective implementation of OELEs, their potential to facilitate divergent and flexible thinking remains provocative. ☐

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This manuscript is based on the doctoral dissertation conducted by the first author at The Florida State University. The authors wish to acknowledge Dr. Marcy P. Driscoll and Dr. Robert A. Reiser of the Instructional Systems Program, Florida State University and Dr. Richard K. Wagner of the Department of Psychology, Florida State University for their cooperation and support as committee members during the conduct of this study. The manuscript was prepared while the first author was working as a post-doctoral fellow at The University of Georgia's Learning and Performance Support Laboratory.

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