Computer-Based Microworlds: A Bridge Between Constructivism and Direct Instruction

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The field of instructional technology is characterized by its products, such as instructional media, and its processes, such as instructional design. Over the past 50 years, the process of instructional technology has been shaped by advances in learning and instructional theory. Much of the development work to date has been associated with direct instruction or instruction based largely on the application of behavioral and neobehavioral principles. In contrast, constructivism, a faction within cognitive psychology associated with Piagetian learning theory, is characterized by discovery and experiential learning. Constructivists have sought to tap the computational power of modern microcomputers to create computer "microworlds," such as those found in LOGO, *in which learners can experience and appropriate sophisticated ideas from (but not limited to) the domains of science and mathematics. Proponents of constructivism and direct instruction usually are viewed in opposition to one another. It is suggested here that each has something to learn from the other, and that computer microworlds offer a platform for collaboration.*

☐ Instructional technology can be defined as the application of what is known about learning and teaching to current instructional practices (Knirk & Gustafson, 1986; Romiszowski, 1981). Instructional technology is, by its very nature, a practical concern, and instructional technologists are essentially educational pragmatists. All share the mission of applying whatever knowledge bases are available to achieve "the goals" of the instructional system. Instructional technology is an evolving and dynamic field which is naturally susceptible to the tension between the many internal forces and perspectives, both current and historical, that seek to define it.

Instructional technology, in its modern form, began as an attempt to apply behavioral learning principles to instruction and quickly merged with the audiovisual movement of the mid-1900s (see Reiser, 1987, for a historical review). Instructional design based on the instructional systems development (ISD) approach has characterized much of instructional technology since World War II (Knirk & Gustafson, 1986). While many people still equate ISD with behavioral learning, many ISD approaches and methods have tried to blend behaviorism and cognitivism in order to achieve learner-centered instruction which is still goal-oriented (Gagné & Glaser, 1987; Hannafin & Rieber, 1989; Merrill, Li, & Jones, 1990a, 1990b). Many are based on accretion or reception learning models, wherein meaningful

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learning is seen as a progression through a series of stages along a continuum from novice to expert (Ausubel, 1968; Mayer, 1984; Norman, 1982) or on a hierarchy from lower-level learning to higher-level learning (e.g., Gagné, 1985). Expert status is achieved through a process by which knowledge is successively acquired and organized and then integrated or "fine tuned" into existing knowledge structures. One might label this approach to instructional technology as "instructivism," because the instructional goals related to one given and supposedly objective interpretation of a domain (i.e., "reality") are still the dominant influence on instructional design, despite the concern and care given to learner abilities and needs.

In contrast to the objectivism of direct instruction is the philosophy of constructivism. Constructivists in education are closely aligned with the theories of Jean Piaget (Butts & Brown, 1989; Forman & Pufall, 1988; Fosnot, 1989; Goodman, 1984; Watzlawick, 1984). At the heart of constructivism is the idea that learning involves individual constructions of knowledge and is accomplished through the process of *equilibration*. *Assimilation* and *accommodation* are the two well-known enabling mechanisms of equilibration. They operate on the natural tension caused by an individual's need for an organized and ordered world while constantly being confronted by the need to adapt to an ever-changing environment (Piaget, 1970; Vuyk, 1981). Constructivists describe learning as occurring through interactions with one's environment or culture. Therefore, the potential for learning at different levels is thought to grow as the environment becomes richer and more engaging for the learner.

The influence of constructivism has only recently begun to spill over to the field of instructional technology. Probably the most well-known computer-based application of constructivism is LOGO, a computer language designed to reflect and promote Piagetian learning (Papert, 1980, 1987, 1988; a more recent example is BOXER [diSessa & Abelson, 1986]). LOGO is a primary example of an application of constructivism based on "microworlds." As the name suggests, a microworld is a small but complete subset of reality in which one can go to learn about a specific domain through personal discovery and exploration (Dede, 1987; Papert, 1981). Papert (1980) suggests that microworlds should fulfill four criteria. They should be simple, general, useful, and syntonic. Syntonic learning means "it goes together with" and suggests that learning is made up of connections, such as connecting new ideas to old. Syntonic learning means going from the "known to the unknown," which is central to every idea in cognitive psychology (Reigeluth & Curtis, 1987). Constructivists assert that these learning connections are initially made possible in a microworld and later enhanced through learner control. This is in contrast to research on learner control of direct instruction, which frequently suggests that learners are often poor judges of their own learning paths (Clark, 1982; Steinberg, 1977, 1989).

The simple premise of this article is that instructional technology in general, and educational computing in particular, have much to gain by the infusion of constructivism into instructional design and that microworlds represent an immediate application. Although microworlds are a constructivist invention, they can provide *goal-oriented* environments in which learning is achieved through discovery and exploration. The compromise is reached largely through a *guided-discovery* orientation to learning in which the nature of the learning activity and experience is naturally constrained by the parameters imposed by a particular microworld. Microworlds offer a compromise between the strict deductive approach suggested by ISD models and pure inductive learning advocated by experiential learning theorists. However, because a microworld's boundaries can be severely limited, the range of learning outcomes also can be constrained, making the achievement of predetermined learning objectives possible and probable, which is the aim of instructivism.

Instructional applications of microworlds conform to the idea of the zone of proximal development (Vygotsky, 1978, 1986), wherein individuals who are on the threshold of learning are often unable to reach understanding without some kind of externally provided assistance or intervention. Similar issues have been discussed by advocates of generative learning (Jonassen, 1988; Wittrock, 1974, 1978) and, more recently, those of situated cognition, who hold that learning should be based (situated) in the context in which it is to be applied (Brown, Collins, & Duguid, 1989). Montague (1988), for example, has applied the "cognitive apprenticeship" model (Collins, Brown, & Newman, 1987) to the design of computer simulations that offer "functional context, performance-oriented" learning environments.

The concept of a microworld is a good vehicle for both reflecting on and working with these issues as they apply to instructional design. Microworlds may also be a good vehicle for enabling others to discuss and understand design issues, since microworlds are often analogous to another computer-based design with which instructional technologists are well acquainted: simulations. At first glance, a microworld appears similar to, if not synonymous with, a simulation. However, a microworld has two essential characteristics which distinguish it from a simulation. First, a microworld embodies the simplest model of a domain that is deemed accurate and appropriate by an expert. Second, it offers an initial point of entry which matches the user's cognitive state so as to allow fruitful interactions to take place. It is this second characteristic which offers a link between constructivism and instructivism.

Designing a microworld to match an individual's needs and level of experience requires a deliberate attempt to structure the microworld in some way. Usually, constructivists limit the learning experience simply by removing the number of variables contained in a microworld, thereby limiting the range of possible experiences with it. For example, LOGO is often introduced to very young children by providing a turtle that responds to single keystrokes and moves and spins in preset increments (such as 10 "turtle steps" and 45 degrees). The resulting mathematical microworld is necessarily constrained in order to increase the likelihood that the child can and will interact with it. Microworlds and simulations can remain mutually exclusive, but this discussion focuses on their similarities in order to propose an applied context in which to understand and apply diverse theoretical positions to instructional design. (See Rieber, in press, for a more detailed account of the differences between microworlds and simulations.)

The purpose of this article is to offer an initial compromise of some old, new, and challenging ideas currently facing instructional technologists. The arguments presented here lie somewhere along the continuum between the pure objectivism of direct instruction and radical constructivism. (The latter contends that each person constructs his or her own "truth" or "reality." Constructivists object when systems, such as schools, try to convey or enforce one interpretation of a set of events onto a learner.) In this article, a working prototype of an instructional computing project is presented, followed by the design considerations which guided its development. The project and the guidelines are based on a merger of the goals and philosophies of constructivism and direct instruction.

TEMPERING DIRECT INSTRUCTION WITH CONSTRUCTIVISM: A PRACTICAL EXAMPLE

Many of the principles of constructivism offer promise in the development of successful learning environments. However, it is difficult to develop practical applications given the typical constraints of most school and training situations (The Cognition and Technology Group at Vanderbilt, 1990, is a notable exception). This dilemma actuated the development of a computer software package called *Space Shuttle Commander* (SSC), which helps elementary and middle school students achieve a wide range of learning goals in the domain of Newton's laws of motion (Rieber, 1990a). This project was founded on compromises such as accepting the constructivist philosophy that learners should be given rich and powerful environments to build and transform mental structures, while acknowledging the instructivist view that instruction must be designed for practical application under existing educational conditions.

SSC is a direct application of a physics microworld designed by Andy diSessa (1982) which involves a dynamic screen object, called a "dynaturtle." The dynaturtle is similar to the more familiar LOGO turtle, except that it has one additional characteristic: velocity. The dynaturtle acts as a free-floating Newtonian particle which students can manipulate. This allows them to explore motion principles in a simulated frictionless, gravity-free environment. SSC adapts this microworld to the context of space travel and, in so doing, the microworld becomes a simulation. In this context, the dynaturtle becomes a "space shuttle" which users have the ability to "command." SSC encourages students to fantasize that they are astronauts aboard the space shuttle.

Other examples of projects based on the dynaturtle microworld include White (1984) and White and Horwitz (1987). There are also many research areas related to the design of microworlds in general (e.g., mental models; see Gentner & Stevens, 1983, and Norman, 1988) and the dynaturtle microworld in particular (e.g., misconceptions in science; see Eylon & Linn, 1988, and Perkins & Simmons, 1988).

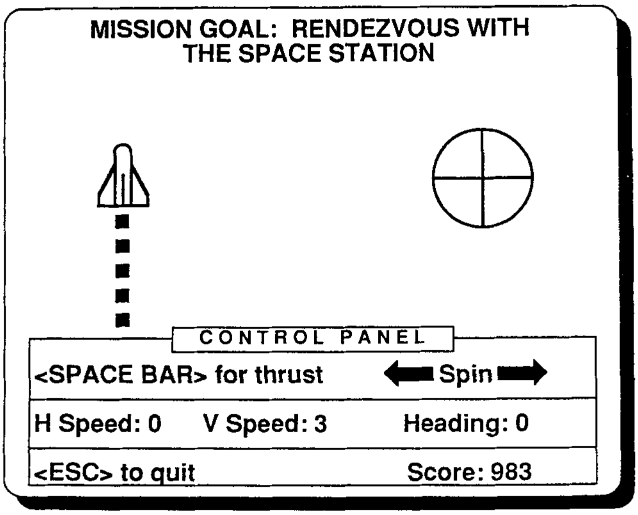
SSC attempts to take advantage of the strengths of tutorials and simulations while minimizing their weaknesses by combining them in a cohesive yet flexible "mini-course." For example, a tutorial is a good way of selecting and presenting content matter in an organized and logical order. However, when based on traditional instructional systems development (ISD), tutorials can be monotonous and tend to promote passive learning at only surface levels (cf. Jonassen, 1988; Merrill, Li, & Jones, 1990a; Roblyer, 1988). Simulations and games offer the potential for intrinsically motivating, discovery-based activities; however, they make the presentation and validation of a predetermined set of learning goals difficult (Alessi & Trollip, 1985; Hannafin & Peck, 1988).

SSC combines the use of computer tutorials and simulations, called "flight lessons" and "missions," respectively. As a tutorial, the flight lessons formally introduce the laws of motion. The flight lessons use a nonmathematical approach that concentrates on concept formation. Designed as a traditional tutorial, the flight lessons are an instructivist invention. The missions comprise a series of simulations with game-like features in which students pilot an animated shuttle, as represented in Figure 1. Portions of both the tutorials and simulations in SSC have been validated through a series of ongoing studies involving the role of computer graphics in learning from animated lesson presentations and visually based simulations (see Rieber, 1990b, for a review). For example, the use of the simulation with elementary school children and adults was found to be generally effective as a practice strategy (Rieber, 1990c; Rieber, Boyce, & Assad, 1990).

Traditional instructional design usually involves strategies that promote deductive learning (Gagné, 1985). For example, a concept or a rule is usually presented to students, followed by examples and nonexamples and practice (Gagné, Briggs, & Wager, 1988). In contrast, constructivists usually encourage inductive learning based on discovery (Bruner, 1966) or "learning by inventing" (Bruner, 1986, p. 127). Through engaged experience in a domain, learners induce, or construct, their own concepts and rules based on their interpretation of the instances encountered. While open to the criticism of oversimplification, the deductive-inductive learning continuum is a useful summary of distinctions between learning environments based on instructivism and constructivism.

In SSC, the activities are designed to follow either a deductive or inductive approach, as well as to allow the provision to switch between each approach. On the surface, SSC is laid out essentially in a deductive fashion, with the tutorials or "flight lessons" organized as a learning hierarchy (Dunn, 1984; Gagné, 1985) where later skills build on earlier ones, as the course map of SSC in Figure 2 shows. Each flight lesson "teaches" the respective objectives according to conventional instructional design and each "mission" acts as a suitable practice activity for each lesson (Gagné, Briggs, & Wager, 1988). Therefore, students can go through SSC in the classic deductive fashion, starting with the first flight lesson.

FIGURE 1 ☐ A Representation of the Computer Screen during an Episode of "Mission 5: Rendezvous." The animated "shuttle" is under student control. Arrow keys rotate the shuttle in 90-degree increments and the space bar gives the shuttle a "kick" or thrust in the direction it is pointing. The goal of this mission is to maneuver the shuttle to the space station. (Not drawn to scale.)



MISSION GOAL: RENDEZVOUS WITH THE SPACE STATION

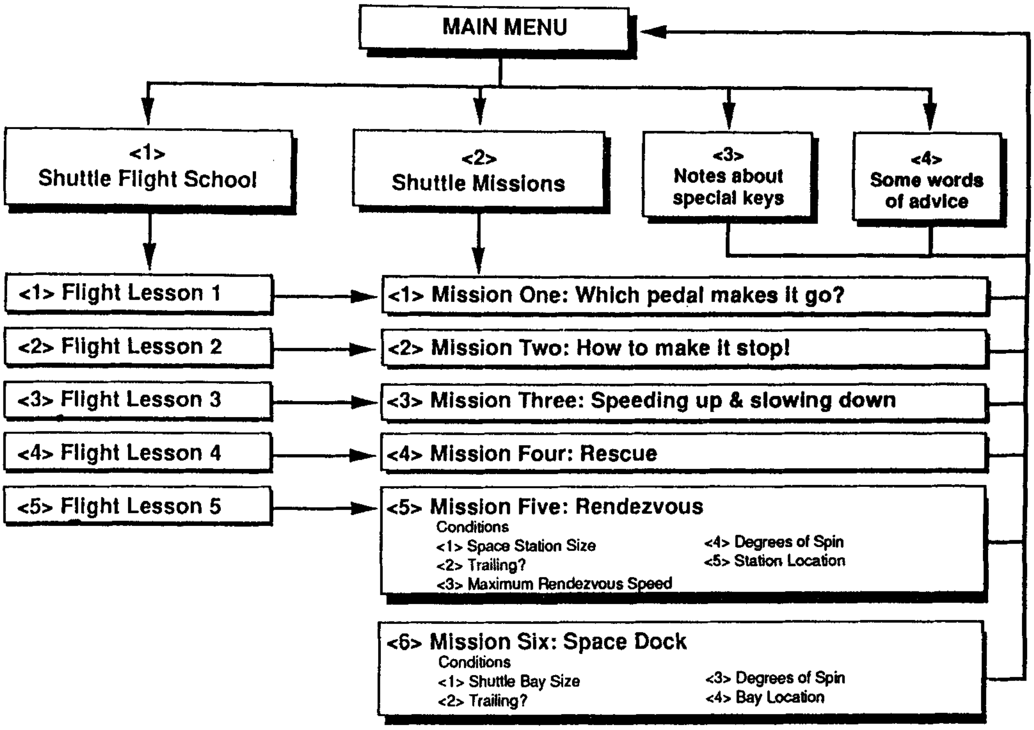
CONTROL PANEL

<SPACE BAR> for thrust ⬅ Spin ➡

H Speed: 0 V Speed: 3 Heading: 0

<ESC> to quit Score: 983

FIGURE 2 ☐ A Course Map of *Space Shuttle Commander.* (Copyright 1990 by Lloyd Rieber.)



However, each mission acts as a stand-alone microworld which simulates one particular aspect of Newton's laws of motion. Early missions are very structured and the number of learning variables is minimized in order to make fundamental ideas and concepts as explicit as possible. Later missions are very open-ended, but with the option for students to impose or reduce structure and complexity. It is possible, therefore, to have students begin to understand Newtonian mechanics by only having them explore the missions in SSC. The flight lessons become resources to provide formal accounts of the information or principles that students actually use on the missions. Flight lessons would be consulted only when clarification is needed, either as the result of curiosity or confusion.

An instructivist would probably interpret the flight lessons as the core of SSC and consider the missions as supporting practice activities. Instructivists would also probably promote the learning hierarchy of SSC. A constructivist, on the other hand, probably would focus on the missions and ignore or disown the flight lessons completely. A constructivist would also let the learner determine sequence. In practice, a combination of deductive and inductive strategies could be used. SSC was designed to let students and teachers make their own interpretations on how it should be used. SSC, like the original dynaturtle microworld, was designed to bring students in contact with ideas for which conventional educational wisdom might indicate they are not yet ready.

SOME INSTRUCTIONAL DESIGN GUIDELINES INFLUENCED BY CONSTRUCTIVISM

Table 1 summarizes a series of considerations in the design of computer-based instruction which can be viewed as a compromise between the instructivist and constructivist perspectives. These principles guided the development of the microworlds contained in the missions of SSC (Boyce, Rieber, & Phillips, 1990). Although these principles can be interpreted many ways, they are primarily offered here to CBI designers as a means to understand and incorporate constructivist goals into their instruction.

These guidelines are presented as a confluence of good ideas from different points of view. Instructional designers who already hold a more cognitive orientation probably will recognize the importance of these guidelines without necessarily connecting them to constructivism. Those who hold a more constructivistic view probably will interpret these as guidelines for microworld design. Instructivists probably will interpret them as useful in the design of cognitively based practice activities.

Provide a meaningful learning context that supports intrinsically motivating and self-regulated learning. Constructivists make two important assumptions about learning in a microworld. First, they assume that the learner will find the completion of the activity to be its own reward. Second, they assume that the learner will take total control and responsibility for the learning experience (Lawler, 1982; Papert, 1980). These assumptions deal with the issues of intrinsic motivation and self-regulated learning.

As the literature on motivation suggests, the degree to which learners demonstrate commitment and perseverance in the thoughtful completion of a task depends on whether the activity is perceived as relevant and its completion as personally satisfying (Keller & Suzuki, 1988; Lepper, 1985). By definition, a meaningful

TABLE 1 ☐ Some Design Considerations for Computer-Based Microworlds

- Provide a meaningful learning context that supports intrinsically motivating and self-regulated learning.
- Establish a pattern whereby the learner goes from the "known to the unknown."
- Provide a balance between deductive and inductive learning.
- Emphasize the usefulness of errors.
- Anticipate and nurture incidental learning.

learning context is an intensely personal affair. The goal in education, however, is to discover contexts that have a wide appeal to learners of varying interests and aptitudes. LOGO, for example, seems to attract the attention of children through the use of interactive computer graphics to produce interesting visual designs.

What motivates an individual to initiate and complete a task? Traditional school and training situations abound with the use of *extrinsic* motivators, such as stars, report cards, or paychecks. In contrast, people tend to complete other tasks without the promise of a reward. Activities are said to be *intrinsically* motivating when a person chooses to participate even after external pressures to do so are removed (Deci, 1975, 1985; Kinzie & Sullivan, 1989; Maehr, 1976). There is even research to suggest that the well-intentioned use of extrinsic motivators, such as grades, can destroy the intrinsic appeal of an activity for some children (see Condry, 1977, Greene & Lepper, 1974, and Lepper, Greene, & Nisbett, 1973, for research on turning "play into work").

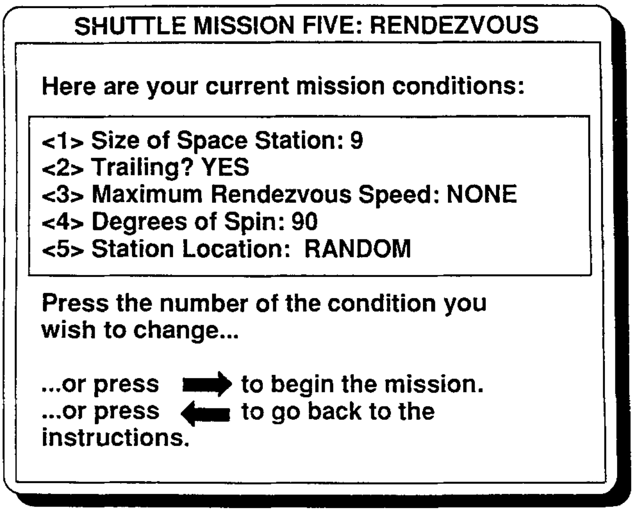
Malone (1981) has suggested a framework of intrinsically motivating instruction based on *challenge, curiosity,* and *fantasy.* Tasks need to be designed to be optimally challenging, such that they are not too easy or too difficult. Perhaps most importantly, tasks should elicit feelings of competence, or self-efficacy, in solving problems which students perceive as relevant and important. This enhances one's self-concept and leads to a feeling of control over one's own success (Weiner, 1979, 1985). Similarly, a person's curiosity is usually piqued when an activity is viewed as novel or moderately complex. Curiosity is also usually increased by activities which offer an element of surprise. This occurs when the expected and actual outcomes of an activity are different or incongruent, a phenomenon which Berlyne (1965) has termed "conceptual conflict." Again, however, both challenge and curiosity produced by a conceptual conflict must be optimally maintained to be effective. A task that is perceived as too easy quickly loses appeal, and a task that is seen as too demanding is avoided. Likewise, a conceptual conflict between expected and actual task outcomes can make a learner seek to resolve the conflict but can quickly lead to frustration if the conflict is too confusing or bewildering.

Norman (1978) has termed optimal levels of conceptual conflict as "critical confusion." Fantasy entails providing learners with a meaningful context for learning which is easy to augment with their imaginations. It is meaningful in the sense that it offers a very personal degree of fascination and intrigue that is easily transferred to play activities. These characteristics of intrinsic motivation are all similar to Keller's (1983) synthesis of affective attributes which form the basis of his Attention, Relevancy, Confidence, and Satisfaction (ARCS) model of motivational instructional design.

SSC, for example, tries to capitalize on the natural fascination and popularity of space travel by encouraging students to fantasize about being the commander of the space shuttle. The purpose of the "missions" is to induce and encourage the fantasy in a series of structured activities, each building on the other. A similar example of using a meaningful context for learning is the *Voyage of the Mimi,* a math and science curriculum set in the context of whale exploration (Bank Street College of Education, 1989). Preliminary research on the missions of SSC support the contention that they hold intrinsically motivating appeal for elementary school children (Rieber, 1991).

An important conclusion of Malone's (1981) research is that students need to be provided with the ability to continually increase the challenge of an activity in order to maintain intrinsic appeal. Several of the SSC missions, for example, provide students with the opportunity to vary the "mission conditions"—target size, target location, shuttle rotation, etc.—in order to increase the difficulty of the activity, as is shown in Figure 3. For example, it is much simpler to control the shuttle in a mission occurring in two-dimensional space when the shuttle's rotation is constrained to 90-degree increments. Control of the shuttle becomes considerably more difficult and complex when control is changed to 45- or 30-degree increments. In addition, a score-

FIGURE 3 ☐ Sample Screen Showing Various Mission Conditions of "Rendezvous." Conditions can be changed to increase the difficulty or context of the mission. (Not drawn to scale.)



SHUTTLE MISSION FIVE: RENDEZVOUS

Here are your current mission conditions:

<1> Size of Space Station: 9
<2> Trailing? YES
<3> Maximum Rendezvous Speed: NONE
<4> Degrees of Spin: 90
<5> Station Location: RANDOM

Press the number of the condition you wish to change...

...or press ➡ to begin the mission.
...or press ⬅ to go back to the instructions.

keeping feature is provided, which is another feature noted by Malone (1981) as increasing intrinsic appeal in computer games.

Successful microworlds rely on students controlling, or self-regulating, their learning. Self-regulated learning can be defined as "individuals assuming personal responsibility and control for their own acquisition of knowledge and skill" (Zimmerman, 1990, p. 3). The advantages of self-regulated learning are obvious. Students not only become more active in the learning process, but also assume responsibility for it. The implication is that students do not simply participate in a given lesson, but actually help to design it. At issue is what instructional designers should consider in helping to nurture the self-regulation process.

As already discussed, intrinsic motivation is an essential characteristic of self-regulated learning; however, self-regulated students are also metacognitively and behaviorally active (Zimmerman, 1990). Metacognitive attributes involve the student's attempt at the planning, goal-setting, and organization of learning, in tandem with self-monitoring and self-evaluation (Borkowski, Carr, Rellinger, & Pressley, 1990). These attributes subsequently lead students to take appropriate actions associated with their own learning, such as the selection, structuring, and creation of environments that will best suit their learning styles and needs. Learning environments, such as microworlds, should be designed with a "self-oriented feedback loop" in which a rich and continual stream of feedback is provided to students to help them establish and maintain goal-setting and goal-monitoring (Zimmerman, 1989). Schunk (1990) referred to a student's deliberate attempts to attend to and evaluate their behavior in relation to their goals as self-observation and self-judgment.

Establish a pattern whereby the learner goes from the "known to the unknown." Meaningfulness can also be interpreted as the degree to which students can link new ideas to prior knowledge, or what the student already knows. The degree to which information is related to prior knowledge is among the most important determinants of learning (Ausubel, 1968). For example, Bruner (1966) suggests a "spiral" approach to learning whereby the simplest and most general ideas are introduced first to learners in highly interactive and concrete ways. These ideas are then successively reintroduced to students at higher levels of abstraction to provide increasing levels of detail. This is similar to Ausubel's (1963) *progressive differentiation* and to Reigeluth's elaboration theory (Reigeluth & Stein, 1983), wherein general ideas grasped early by learners help them to subsume more detailed ideas introduced later.

SSC can act as a bridge between experiential learning with a dynaturtle and formal physics (as usually taught in schools). Paradoxically, traditional physics instruction based on highly mathematical models usually removes the influences of friction and gravity in order to "simplify" learning for students. While mathematical formulas are simplified using this convenience, students' conceptual understanding is usually muddled, since the removal of friction and gravity is totally outside of their daily experiences. SSC tries to provide students with a sound conceptual understanding of Newtonian principles to act as "anchoring posts" for subsequent instruction.

In addition, the simulated space shuttle, like its cousin the dynaturtle, acts as a transitional object between the learner and Newtonian physics, thereby acting as an "object to think with" (Papert, 1980). The search for other good objects to think with—pots, pans, mud pies, etc.—is at the heart of a constructivist approach to learning. Meaningful interaction with objects in the environment liberates and encourages the equilibrium process.

Provide a balance between deductive and inductive learning. Historically, ISD approaches are based on deductive learning models wherein the instructional goal is to identify a set of learning objectives as precisely as possible and bring the learner to mastery of those objectives as directly and efficiently as possible (Reigeluth, 1983). Students are given a set of "truths" to learn and apply. For example, a rule such as Newton's first law is explicitly presented with a variety of supportive examples and activities. Students then practice using and applying the rule and eventually are tested on their understanding. If mastery is achieved, students proceed to the next objective in the hierarchy; if mastery is not achieved, the students are either provided with remediation on the objective or are exited to receive instruction on prerequisites (Dick & Carey, 1985). In contrast, a constructivist approach involves largely inductive strategies whereby instances of a rule are provided with the goal that the learners will induce the rule for themselves. By so doing, learners make each "truth" they discover their own. The supposition is that this approach leads to deeper levels of understanding and also that it intrinsically motivates students to persist in the task.

The problems with extreme interpretations of either approach are obvious. Strict deductive approaches can lead to instructional designs that are unnecessarily self-limiting and inclined to assign a passive role to the learner. Instructional designs are likely to resemble one another, resulting in activities that lack imagination and innovation. Deductive approaches are much easier to apply when learning outcomes involve verbal information, because there is little need for interpretation or inference on the part of the learner. Conversely, strict inductive approaches resemble a "sink or swim" philosophy that can cause learners to become bored or frustrated if they are unable to generalize from the instances provided.

In addition, novices often need structure or guidance which purely inductive experiences do not provide, a problem frequently encountered by designers of hypertext (Jonassen, 1986; Tripp & Roby, 1990). Inductive activities also require an attitude of playfulness and exploration which older children and adults may resist. Adults should be properly oriented to assure them that the activity has a purpose and "that their experimental behavior will not be held against them" (Seaman & Fellenz, 1989, p. 97). This is especially important when the inductive activity calls for the grouping of participants, such as in cooperative learning. It is important that aggressive or highly competitive group members do not threaten other group members (Seaman & Fellenz, 1989).

Emphasize the usefulness of errors. Errors are an inevitable part of the learning process, especially at higher levels of learning, such as problem solving (Fredericksen, 1984; Schimmel, 1988). Inductive learning theories promote the ability of learners to detect errors and then incorporate the information learned in subsequent trials. Using errors in inductive learning is not meant to be a haphazard process, but is usually quite systematic, like the "debugging" process in computer applications. When confronted with the task of learning about two or more unknown variables, a learner must be able to isolate and manipulate each of the variables while holding all other variables constant. This systematic process of error handling forms the basis of hypothesis forming and testing, as shown in the research on concept formation (see Mayer, 1983, for a review). The ability of a learner to focus on one variable at a time while understanding the relationship among two or more variables is an example of decentered thinking (as compared to egocentric thinking), of which the ability to conserve is an example (Slavin, 1988).

Unfortunately, many learning tasks contain so many individual variables that a novice would soon be inundated with information to the point of frustration. Microworlds offer a way to structure a learning experience so that a finite set of variables can be introduced at any one time. Once these variables are mastered, additional variables can be introduced. Piaget called this *variable stepping*, which is an essential characteristic of forming and testing hypotheses. In classical mechanics, for example, problems can be simplified when presented in one rather than two dimensions. In a computer microworld, such as the SSC missions, simplification is accomplished in a number of ways. Certain computer commands can be activated or deactivated, depending on which variables are to be explored in a particular activity. Other commands can be constrained so as to produce a particular effect, such as limiting the rotation of the shuttle to 180-degree increments so that one-dimensional motion is produced.

Errors cannot be useful unless the goal of an activity is clearly known (Norman, 1988). If the goal is ambiguous, then all available feedback will also be ambiguous. In LOGO, for example, students often work toward the completion of a graphic they have chosen, such as a house or a car. The graphical feedback they receive from the turtle is continually judged against their individually defined goals. In the best of cases, goal monitoring is automatic and intrinsic (Schunk, 1990). The best rule of thumb for microworld design is to provide the simplest and clearest goals. An example of a mission goal in SSC is "fly the shuttle to the space station."

Finally, a variety of feedback features can also be used to complement one another. For example, the shuttle in SSC automatically leaves a trail in order to show the history of its travel path (although this feature can be turned off, since many people find the trails distracting at times). Verbal feedback can also be presented in tandem with visual feedback. SSC provides a "control panel" showing such information as the shuttle's heading and vertical and horizontal speed. Verbal feedback can be important when novices have difficulty seeing slight visual changes, such as when the shuttle is moving very slowly. The role of errors in learning is a distinguishing feature between behavioral and cognitive learning perspectives.

Anticipate and nurture incidental learning. A key strength of the constructivist approach is that learning does not necessarily flow from a fixed sequence of ideas. In LOGO programming, for example, mistakes or "bugs" often lead to interesting phenomena and students often choose to abandon an original programming project in favor of projects that follow up on unexpected results. However, this can make it difficult to identify and document achievement of learning goals or competencies. In contrast, instructivist approaches strive to take a group of learners through a sequence of predetermined learning objectives to the point of ignoring any learning that may be incidental to these objectives. Learners are not only less likely to explore a wider array of learning experiences, but are actually discouraged from doing so.

Carefully designed microworlds should expect and encourage incidental learning to occur within design parameters. The teacher's role is very important here. A teacher can help to channel incidental learning to serve the lesson or unit's terminal goals by helping to illustrate their relevancy. Likewise, students are apt to get sidetracked by incidental paths, and a teacher should redirect a student back to relevancy if the incidental learning is too esoteric or counterproductive.

One example of the two edges of the incidental learning "sword" is provided in the research by Rieber (1991), in which incidental learning from the tutorial sections, or "flight lessons," of SSC was studied. Students in the study were given a tutorial on a simple application of Newton's second law, wherein the acceleration of an object with a constant mass varies depending on the force that is applied to it. However, students given an animated account of this principle also were taught another application of this physics law incidentally. Through animation, students saw the motion consequences when the same size force is applied to objects of different mass. Fourth-grade students successfully extracted this incidental application even though no formal attempt was made to teach them the rule. However, these students continued to apply this incidental information to other *inappropriate* contexts, such as gravitation problems. The conclusion is that students who learn in incidental ways apply this information in a variety of contexts, some of which may be appropriate and constructive to a larger set of learning goals and some of which may actually undermine some learning goals, such as by promoting misconceptions. (See Klauer, 1984, for a review of issues related to incidental learning.)

CONCLUSION

The educational dilemma of promoting a constructivist philosophy within an educational system based on direct instructional methods is discussed in this article. The dilemma is not necessarily the paradox it appears to be. Rather than being a destructive influence on instructional technology, the tension caused by this dilemma is healthy and useful as well as necessary in the maturation of the field. Tension acts as a "dithering device" which motivates reflectivity and growth and helps to eliminate stagnation and professional nepotism. Instructional technology must remain eclectic to be effective. The ability to learn and otherwise progress in cognitive ways is a natural, innate, and *personal* process for people, and one which the constructivist approach advocates. However, extreme interpretations of constructivism can lead to instructional chaos. The instructivist approach sees learning as the mastery of a series of objectives, with the mastery of one objective serving as the starting point for the next. However, this approach risks the danger of focusing on the content to be learned instead of the learner and the learning experience.

It is suggested that computer microworlds offer an interesting compromise between the instructivist and constructivist approaches. Microworlds can be designed in such a way as to give users exploratory experiences within a carefully controlled range of concepts and principles, and thereby offer a practical compromise between instructivism and constructivism. *Space Shuttle Commander* is offered as one preliminary attempt to put these ideas into action. ☐

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